«Короткодействующие нуклонные корреляции и EMC эффект»

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Гатчина, 7 апреля, 2022

Outline

- *A rather long Introduction: what we see depends on how we look*

- *Properties of short range correlations*

- *Observation of 2 nucleon SRC in hard processes*

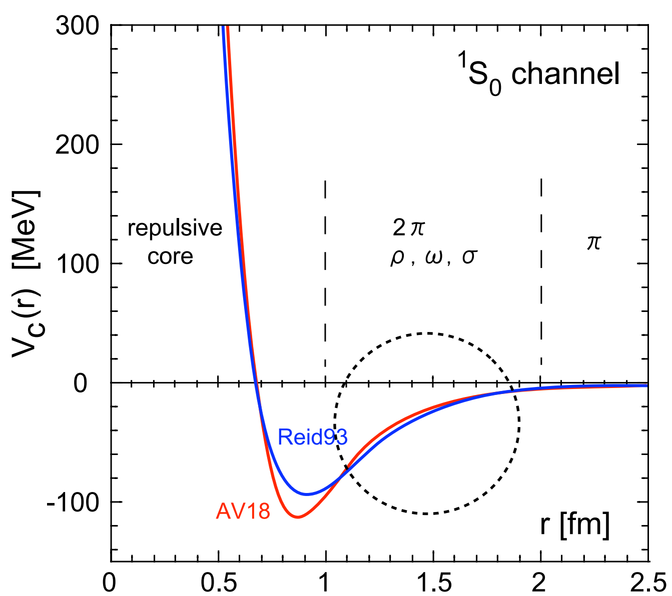
- *EMC effect [observed so far of only for quarks in nuclei]*
  - from 100 models to one class of models

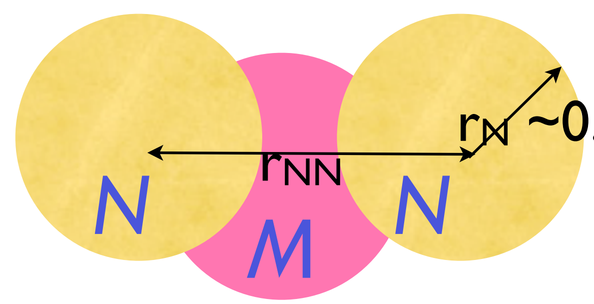
Personal history remark

Leonya Frankfurt (LF) and me -both with background in particle physics became interested in nuclei in mid 74. Quarks have been seen - definitively - DIS, J/ψ.

Where are quarks in nuclei?

Before QCD - paradox - strength of meson nucleon interaction increases with virtuality in the meson-nucleon field theoretical models: *zero charge (Landau) pole is present at rather small virtualities. No trace of this effect in NN and πN interactions. Even without the zero charge pole - interaction is very strong - why nucleus is not a meson soup?*

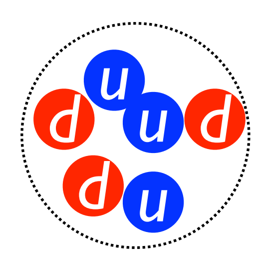




r_N ~0.6 fm for valence quarks

For r_{NN}< 1.5 fm difficult to exchange a meson; valence quarks of two nucleons start to overlap

Perhaps a quark soup for r_{NN} < 1.2 fm?



quark kneading (FS75)

became popular under name six quark bags

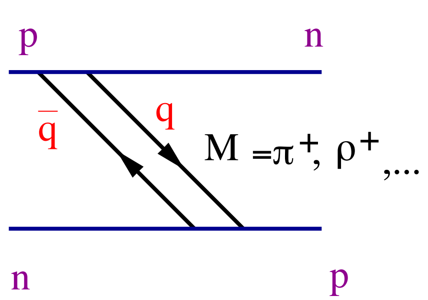
quark and gluon interchanges?

QCD - medium and short distance forces are at distances where internal nucleon structure may play a role - nucleon polarization/ deformation (same or larger densities in the cores of neutron stars). Surprisingly small for quarks (EMC effect)

In spite of each nucleon having a neighbor
at r_{NN}< 1.2 fm!! at average nuclear density, ρ_0

Are quark, gluon interchanges dual to meson exchanges?

Could be for low resolution scale but not for a hard scale



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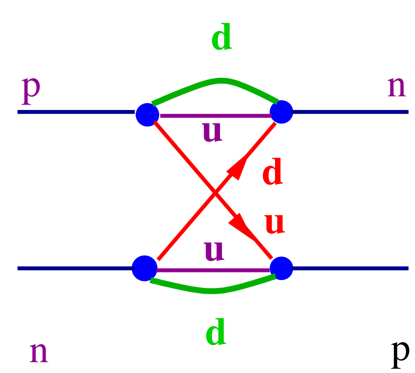


Intermediate state may not be = pn, but say ΔN.

Meson Exchange

Quark interchange

extra antiquarks

Our prime motivation was: quarks were seen in DIS - large momentum transfer processes - can one perform similar program in nuclei and see constituents of the nucleus?

On experimental side: first data on large Q^2 momentum transfer reactions with deuteron emerged only a year later.

However there was a puzzle in hadronic interactions.

Modern formulation *(actual measurements at fixed targets with proton, photon, pion nuclear beams)*:

Consider collision of nuclei A_1 and a proton at a collider - RHIC with $E_A/A= 100$ GeV

- ☛ *nucleons with E_N up to 300 GeV are observed*

- ☛ *shape of the spectra for $A={}^4He$ and $A=Pb$ are practically same up to 200 GeV*

suggested some local / short range dynamics

Fundamental questions about microscopic quark-gluon structure of nuclei and nuclear forces

- Are nucleons good nuclear quasiparticles?

- Probability and structure of the short-range correlations in nuclei

- Microscopic origin of intermediate and short-range nuclear forces

- What are most important non-nucleonic degrees of freedom in nuclei?

Experience of quantum field theory - interactions at different resolutions (momentum transfer) resolve different degrees of freedom - renormalization,.... No simple relation between relevant degrees of freedom at different resolution (virtuality)scales.

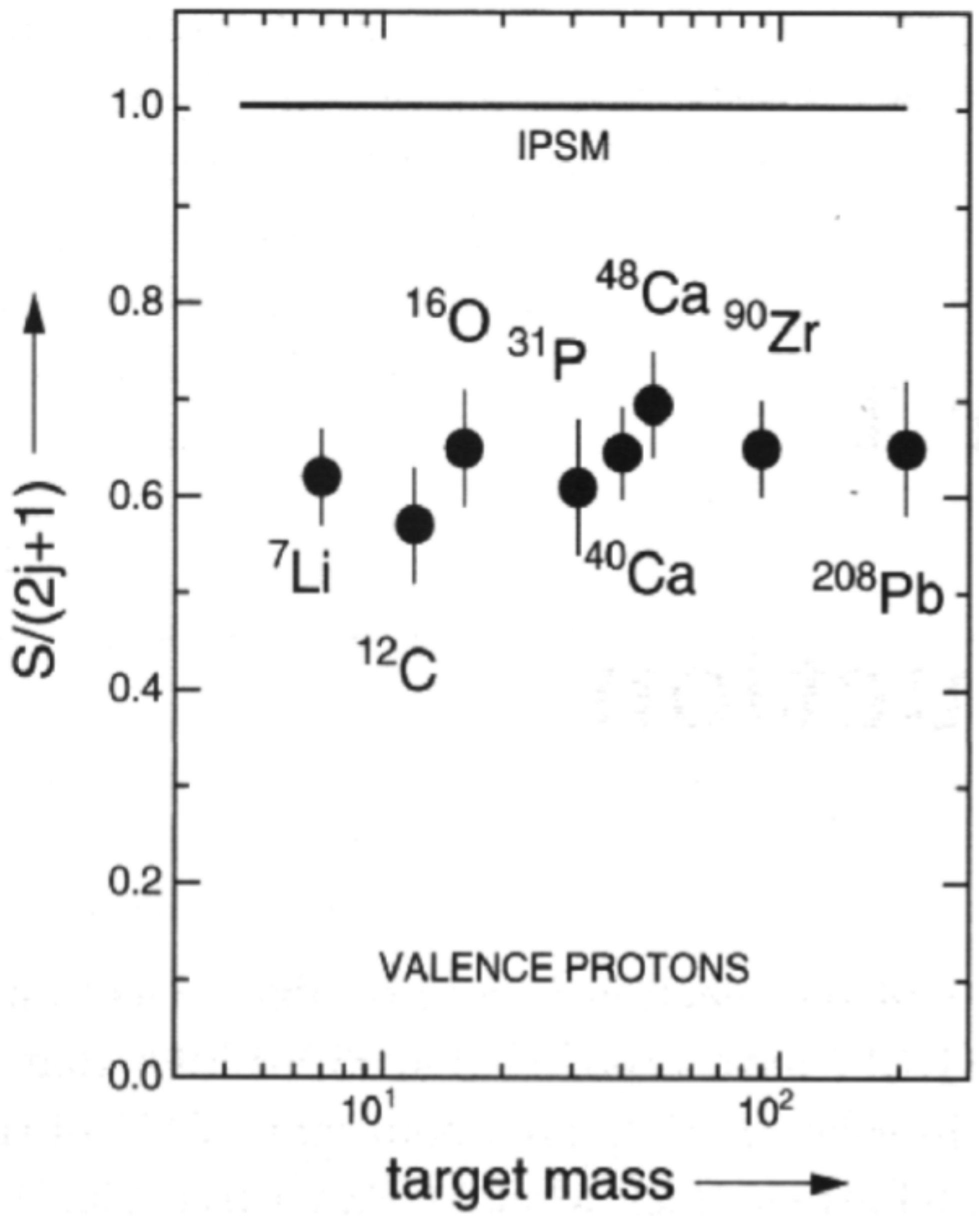
$\boxed{\Rightarrow \text{Complexity of the problem}}$

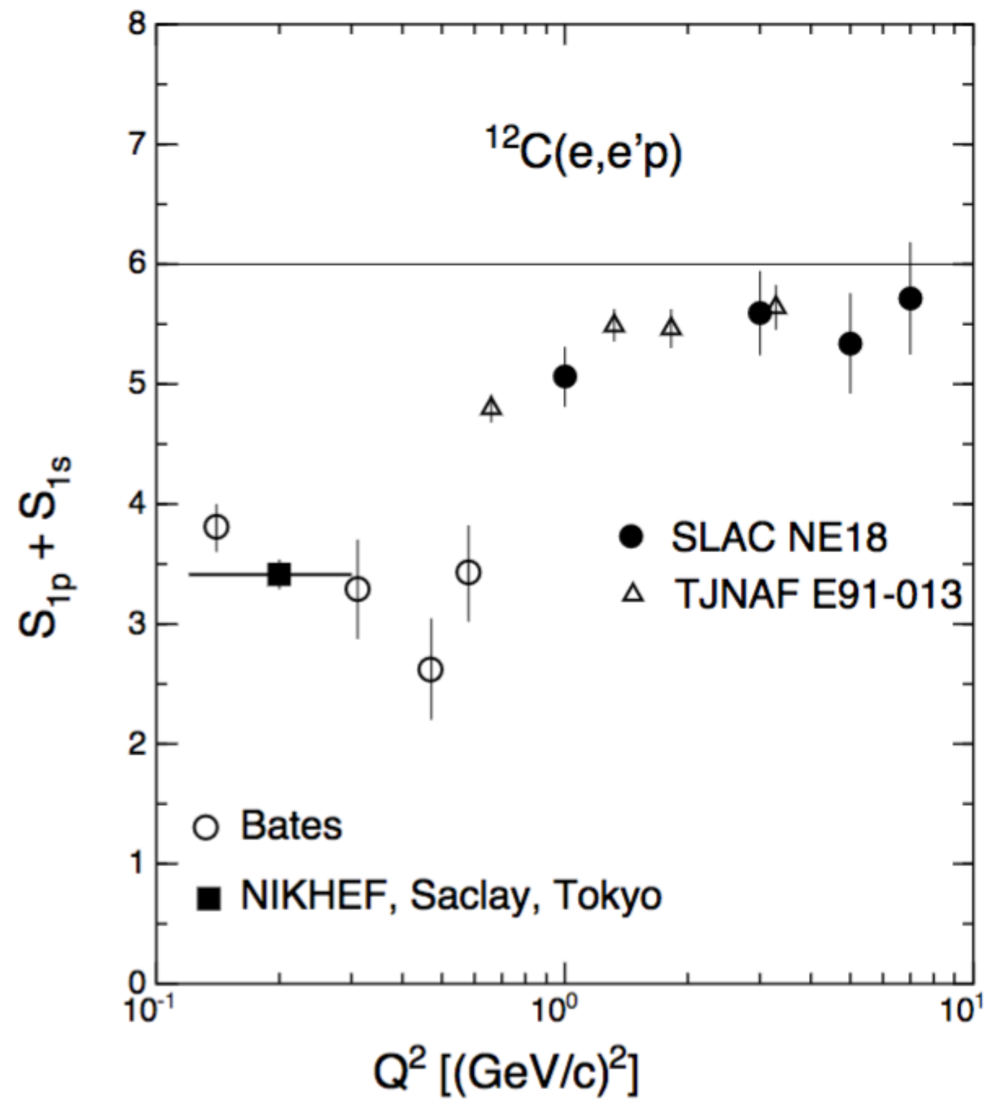
Three important scales

① To resolve nucleons with $k < k_F$, one needs $Q^2 \geq 0.8$ GeV^2.

related effect: Q^2 dependence of quenching, Q

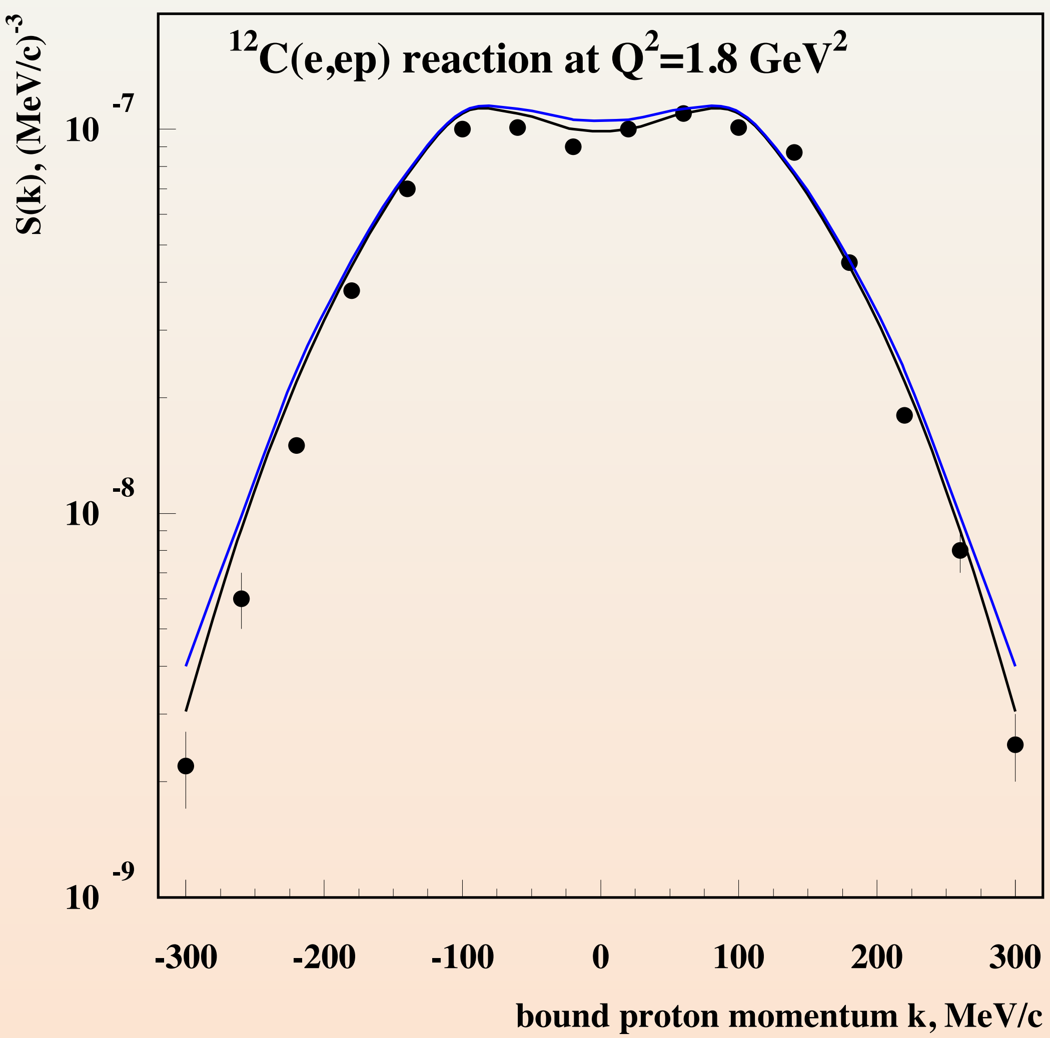
related to the rate of eA—> e'p(A-1) process

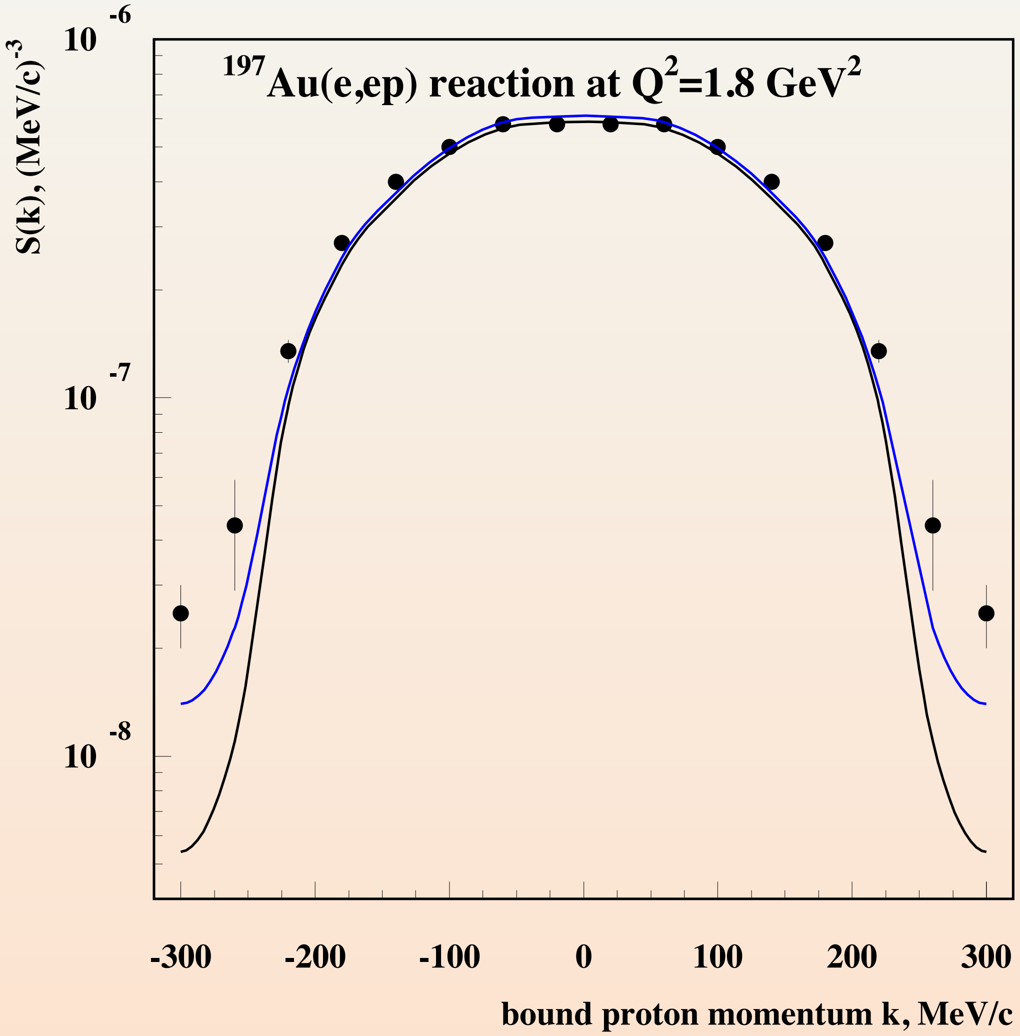




L. Lapikas, G. van der Steenhoven,
L. Frankfurt, M.~Strikman, M. Zhalov, 99

Eikonal approximation usually neglects change of the transverse nucleon momentum in the final state rescatterings. We checked that account of this effect leads to a small correction for k<200 MeV/c





FSZ2000; data from D. Dutta et.al.

② Hard nuclear reactions I: energy transfer > 1 GeV and momentum transfer q > 1 GeV.

$$q_0 \geq 1GeV \gg |V_{NN}^{SR}|, \vec{q} \geq 1GeV/c \gg 2\ k_F$$

Sufficient to resolve short-range correlations (SRCs) = direct observation of SRCs but not sensitive to quark-gluon structure of the constituents

Principle of resolution scales (FS 76) was ignored in 70's, leading to believe SRC could not be unambiguously observed. Hence very limited data

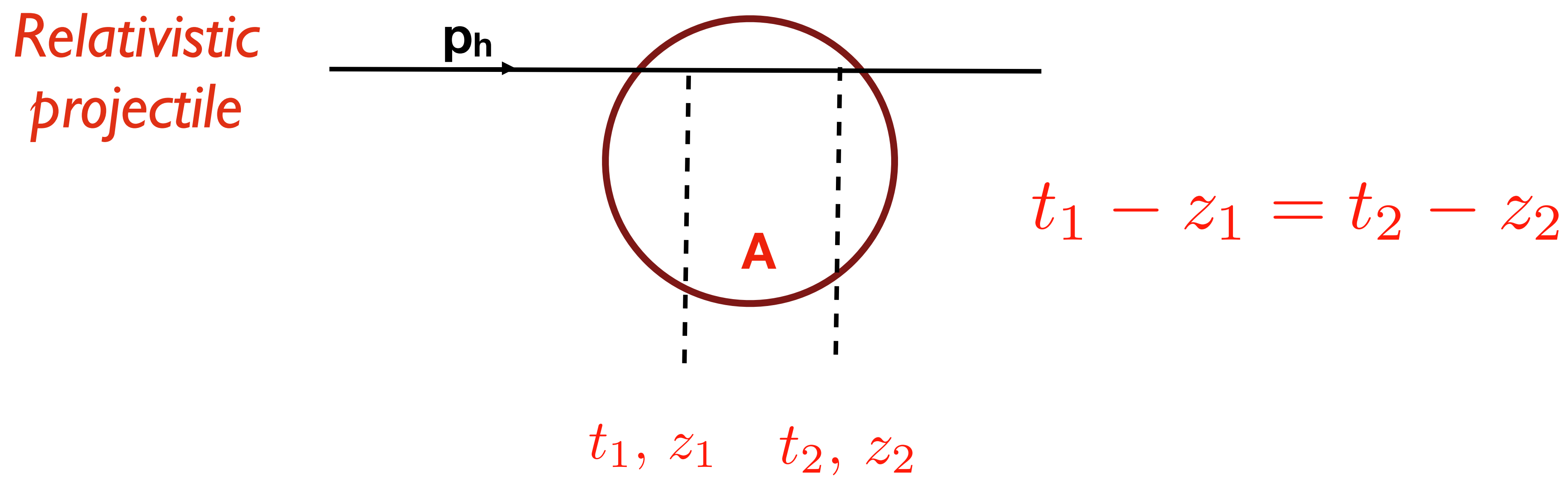
Historical remark: in 70's it was considered hopeless to look for SRC experimentally, hence Phys.Lett. rules (informal) stated to us by the editor were to reject claims to the opposite without peer review

③ Hard nuclear reactions II: energy transfer ≫ 1 GeV and momentum transfer q ≫ 1 GeV. May involve nucleons in special (for example small size configurations). Allow to resolve quark-gluon structure of SRC: difference between bound and free nucleon wave function, exotic configurations

$\Rightarrow$

Hence one has to treat the processes in the relativistic domain. The price is a need to treat the nucleus wave function using light-cone quantization - - One cannot use (at least in a simple way) nonrelativistic description of nuclei as well as covariant approaches. (More about this in the second part of the talk (EMC effect…)

$\Rightarrow$ High energy process develops along the light cone.



Similar to the perturbative QCD the amplitudes of the processes are expressed through the wave functions on the light cone. In the nucleus rest frame

$$\alpha_N = (E_N - p_{N\,z})/(m_A/A)$$

In the reference frame of collider (LHC,RHIC) $\alpha_N = AE_N/E_A$

Kinematics is much simpler in LC variables. Example: $\gamma + D \to N + X$

$$p_N^{max} = \frac{3}{4} m_N \iff \alpha_N^{max} = 2$$

Note: in general no benefit for using LC for low energy processes.

$$\alpha = (\sqrt{p^2+m^2} - p_3)/(m_D/2)$$

where p is rest frame momentum of nucleon spectator in reaction h+ D—> p +X

$$\alpha = 1 + k_3/\sqrt{m^2+k^2}$$

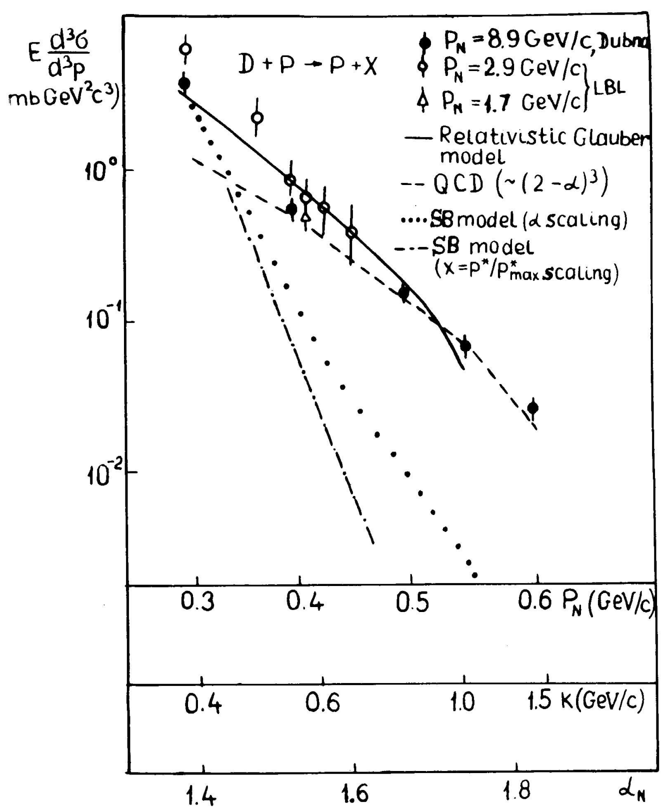
For variable k, LC bound state eqn is very close to NR one

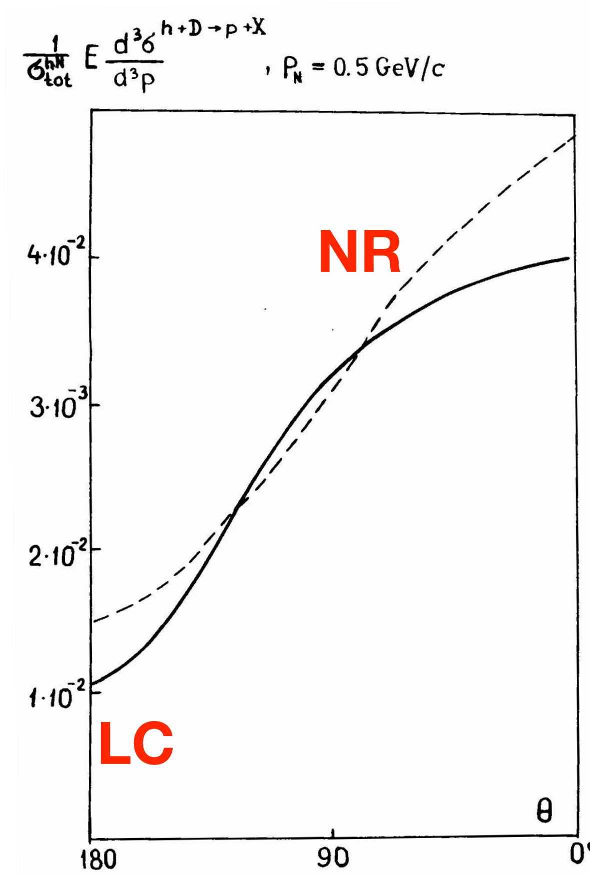
Highly nonlinear relation between momentum k and momentum p: backward p=3m/4 ⟷ $k \to \infty$

backward p=0.5 GeV—> k=0.8 GeV

$$\frac{d\sigma(p+D\to p+X)}{d^2k_t d\alpha/\alpha} = \sigma_{NN}^{inel}\psi_D^2(\alpha,k_t)$$

large momentum transfer in NN scattering, spectator mechanism -decay function



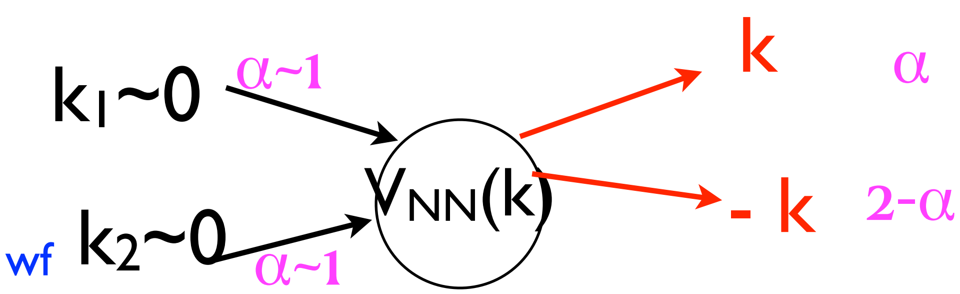


would be highly desirable to have data from Jlab (real photon, moderate x ~.1- .2), etc

Properties of SRCs

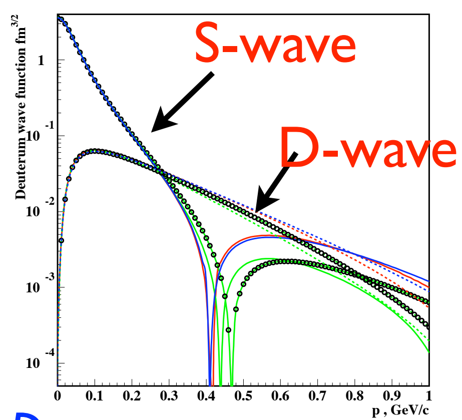
Realistic NN interactions - NN potential slowly (power law) decreases at large momenta -- nuclear wf high momentum asymptotic determined by singularity of potential:

$$\psi^2_D(k)_{|k\to\infty} \propto \frac{V^2_{NN}(k)}{k^4}$$



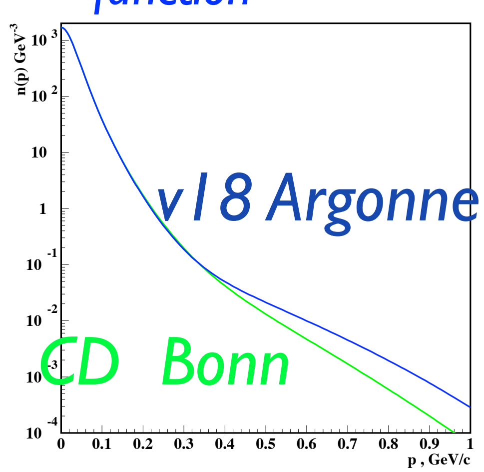
D-wave dominates in the Deuteron wf for 300 MeV/c < k < 700 MeV/c

D-wave is due to tensor forces which are much more important for pn than pp



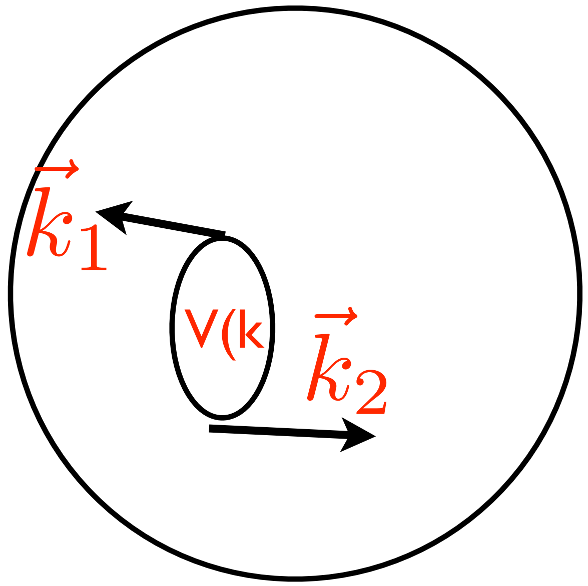
Deuteron wave function

Tensor forces are pretty singular ➟ manifestations very similar to *shorter* range correlations - so we refer to both of them as SRC



Large differences between in $n_D(p)=\psi^2_D(p)$ for $p>0.4$ GeV/c - absolute value and relative importance of S and D waves between currently popular models though they fit equally well pn phase shifts. Traditional nuclear physics probes are not adequate to discriminate between these models.

Natural expectations - summary:



Two nucleon SRC

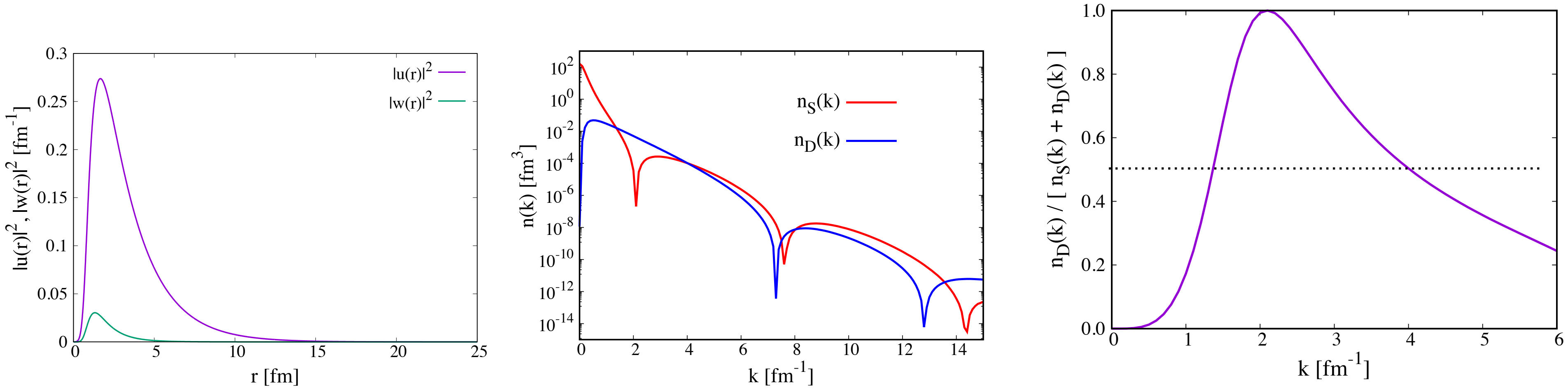
$$\vec{k}_1 + \vec{k}_2 \approx 0$$

$k_1 > k_F$ Dominant contribution for large k; universal (A-independent up to isospin effects) momentum dependence

- ☛ SRCs in different nuclei have approximately the same structure on nucleonic and quark level which should depend on isospin of SRC (I=0 & I=1).

- ☛ *deviations from many nucleon approximation are largest in SRC*

A quick look at coordinate and momentum deuteron wave functions



D-wave dominates in momentum space between 300 and 800 MeV/c in spite of being much smaller than S wave at all distances. High momentum tail in this region is due to Fourier transform of rapidly changing integrand.

No simple relation "high momentum — small distance"

Is w(k) /u(k) universal for k> 300 MeV/c?

No direct calculations so far.

Dynamical quantities (ones which can be directly observe)

Nonrelativistic	**Light cone**
momentum distribution **n(k)** *not observable directly*	LC density matrix $\rho_A(\alpha, k_t)$

calculated for A=3 and nuclear matter → **Spectral function** **$P_A(k,E)$**

modeled in 2N moving in mean field model (next slide)

Decay function

$$D_A(k_2, k_1, E_r) = |\langle \phi_{A-1}(k_2, ...) \, | \delta(H_{A-1} - E_r) a(k_1) | \, \psi_A \rangle|^2$$ **FS81 -88**

Ab-initio NR calculation of double momentum distribution + ansatz 2N moving in mean field are used for modeling spectral and decay functions

Can one check whether indeed the n(k) high momentum tail is due to SRCs?

Consider distribution over the residual energies, E_r, for A-1 nucleon system after a nucleon with momentum k was instantaneously removed - nuclear spectral function

$$P_A(k, E_r)$$

- probability to find a nucleon in a nucleus with momentum k, and after instantaneous removal find the residual A-1 system with excitation energy E_r

$$n(k) = \int dE_r P_A(k, E_r)$$

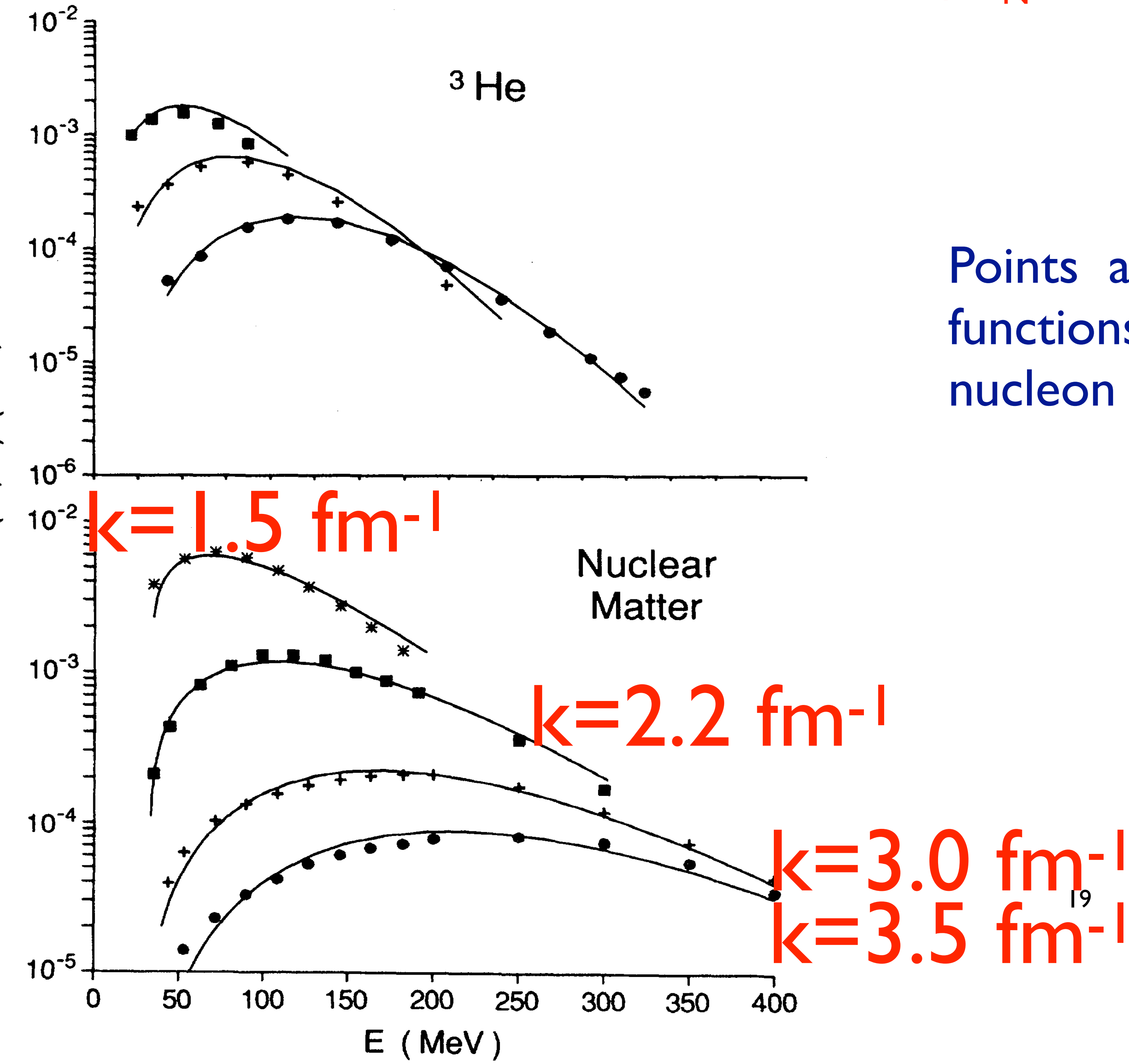
FS81-88

for 2N SRC: $\langle E_R(k) \rangle = k^2/2m_N$

Confirmed by numerical calculations shown before

Numerical calculations in NR quantum mechanics confirm dominance of two nucleon correlations in the spectral functions of nuclei at k> 300 MeV/c - could be fitted by a motion of a NN pair in a mean field (Ciofi, Simula,Frankfurt, MS - 89-91). However numerical calculations for nuclear matter ignored three nucleon correlations - 3p3h excitations.

Relativistic effects maybe important rather early as the recoil modeling does involve k^2/m_N^2 effects.



Points are numerical calculation of the spectral functions of ^{3}He and nuclear matter - curves two nucleon approximation from CSFS 91

For power law potentials expect for momentum distribution: $n_A(k)$:

$n_A(k)/n_D(k)$ —> const for k—>∞

Agrees with modern calculations. Calculations sum over all partial waves - so no direct confirmation of D-wave dominance

$\alpha \geq 2$ —> 3N SRC. Actually $\alpha > 1.6$. In LC higher order correlations are explicitly seen already on a single particle momentum distribution level - (not the case for n(k)

Proportionality of $\rho_A^N(\alpha, p_t)$ and $\rho_D^N(\alpha, p_t)$ for $1.3 \leq \alpha \leq 1.6$

Standard model first developed in the analysis of the BNL pA -> ppn + X experiment and perfected by the MIT group: SRC described as universal pn, pp, pairs moving in mean field

Additional Ansatz - LC implementation of motion of the pair in the mean field

symmetry in LC NN fraction around α_{NN}=2

question/concern: removing one nucleon from fSRC does not destroy interactions of second nucleon of SRC with mean field - *should suppress emission from pairs with high momenta of the pair.*

UNIVERSALITY

Scaling of the ratios of (e,e') cross sections

Qualitative idea - to absorb a large Q at x>j at least j nucleons should come close together. For each configuration wave function is determined by *local* properties and hence universal. In the region where scattering of j nucleons is allowed, scattering off j+1 nucleons is a small correction.

$$\sigma_{eA}(x,Q^2)_{x>1} = \sum_{j=2} A\frac{a_j(A)}{j}\sigma_j(x,Q^2) \qquad \sigma_j(x>j,Q^2)=0$$

$$a_j(A) \propto \frac{1}{A}\int d^3r\rho_A^j(r) \qquad a_2 \sim A^{0.15}; \qquad a_3 \sim A^{0.22}; \qquad a_4 \sim A^{0.27}$$ ***for A> 12 if Z=A/2***

$$\sigma_{A_1}(j-1<x<j,Q^2)/\sigma_{A_1}(j-1<x<j,Q^2) = (A_1/A_2)a_j(A_1)/a_j(A_2)$$

Scaling of the ratios FS80

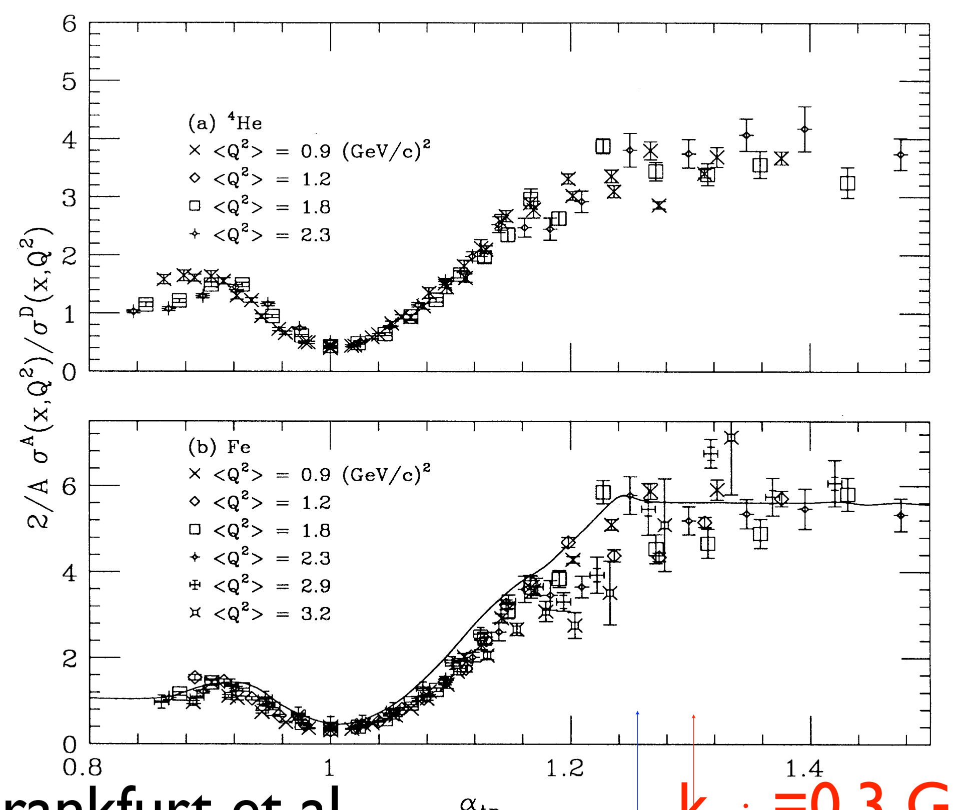
CONFIRMATION of UNIVERSALITY

Superscaling of the ratios FS88

α_{tn} is α for scattering off pair at rest

$$\Rightarrow \quad \frac{\sigma_{A_1}(x,Q^2)}{\sigma_{A_2}(x,Q^2)} = \frac{\int \rho_{A_1}(\alpha_{tn},p_t)d^2p_t}{\int \rho_{A_2}(\alpha_{tn},p_t)d^2p_t} = \frac{a_2(A_1)}{a_2(A_2)}\Big|_{1.6>\alpha\geq 1.3}$$

Note - local FSI interaction, up to a factor of 2 for σ(e,e'), cancels in the ratio of σ's

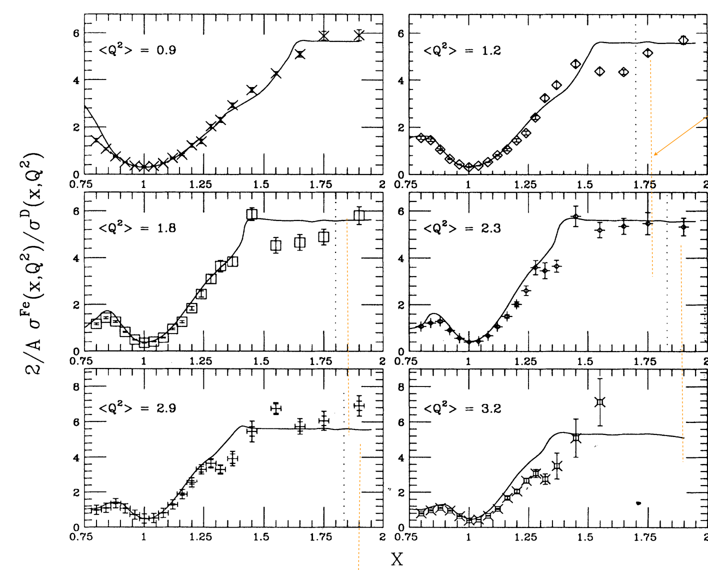


Frankfurt et al, 93

k_{min}=0.3 GeV

k_{min}=0.25 GeV

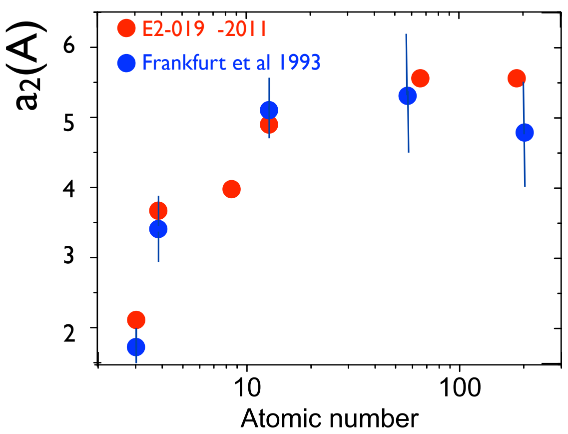
$W - M_D \leq 50\,MeV$



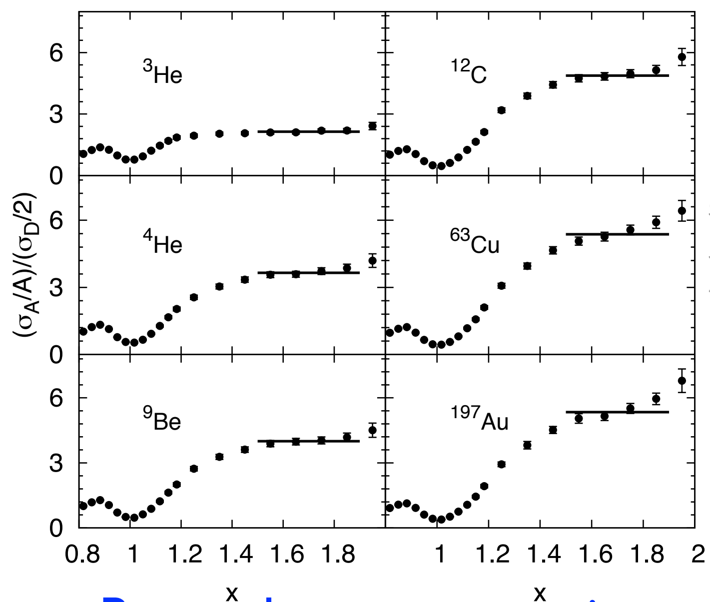
Masses of NN system produced in the process are small - strong suppression of isobar, 6q degrees of freedom.

Right momenta for onset of scaling of ratios !!!

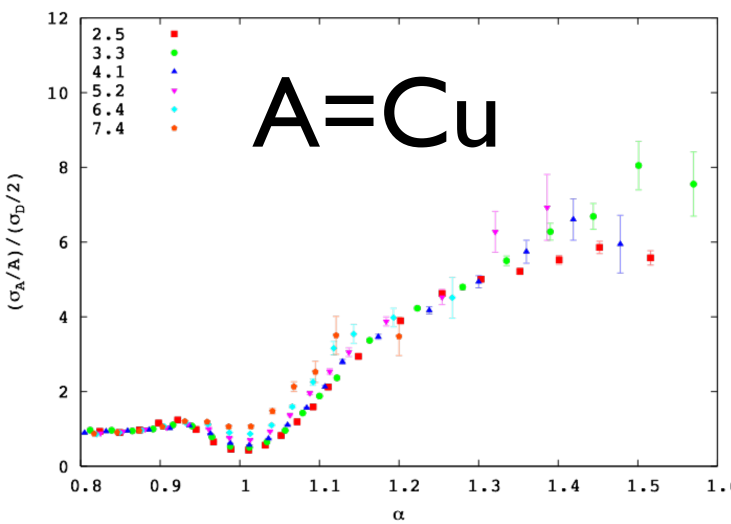
Universality of 2N SRC is confirmed by Jlab experiments



Probability of the high momentum component in nuclei per nucleon, normalized to the deuteron wave function



Per nucleon cross section ratio at Q^2=2.7 GeV^2 - E2-019-2011



From N.Fomin thesis
E2-019-2011

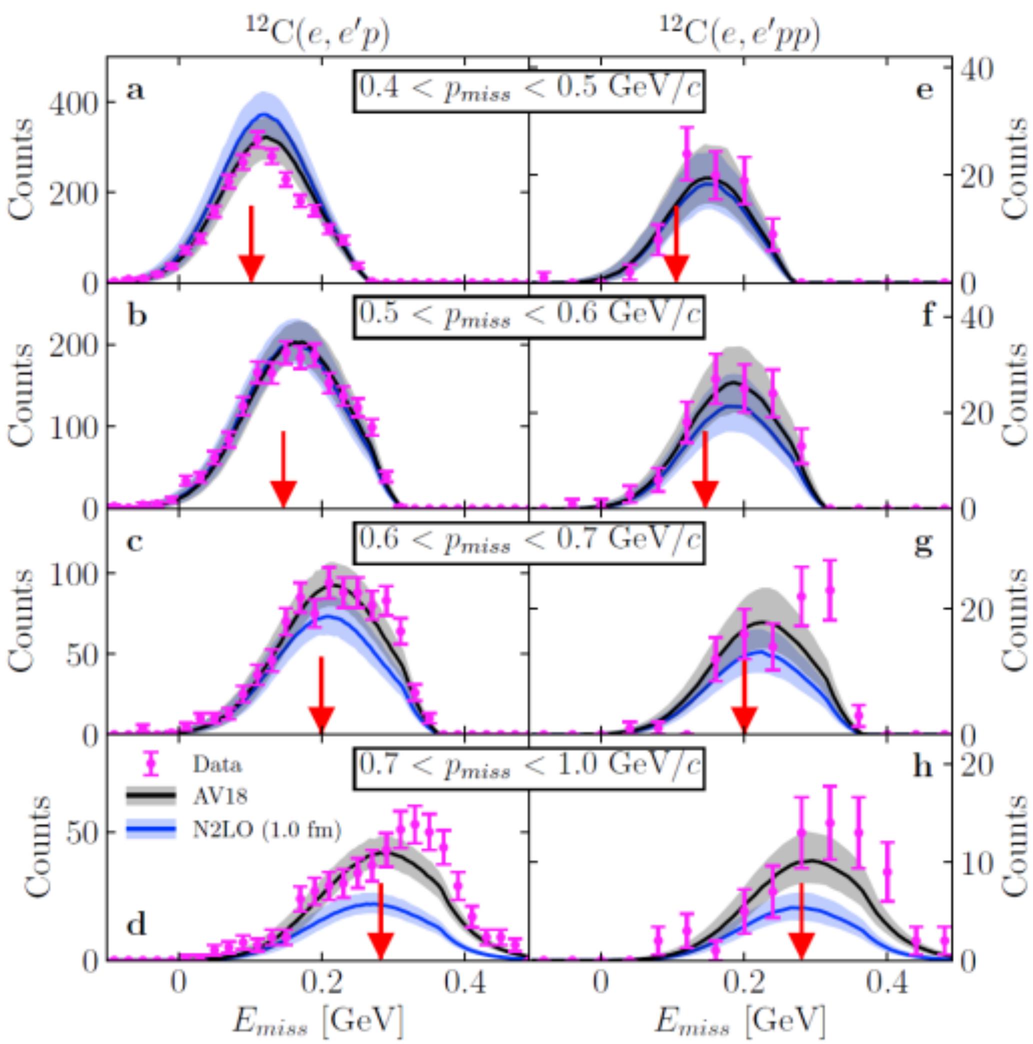
Very good agreement between three (e,e') analyses for $a_2(A)$ as well as recent CLAS data.

So far Jlab experiments marginally reach 3N correlation region but they are consistent wi prediction of

probability 3N SRC =a_3 , satisfying $a_3(A) \propto [a_2(A)]^2$

Testing spectral function

Nature



Data mining. Group with participation of a few theorists

E_{miss} dependence of the ^{12}C(e,e′p) (left) and ^{12}C(e,e′pp) (right) reactions for different p_{miss} values. The red arrow indicates the expected E_{miss} for a breakup of SRC pair with p_{CM}=0 and a missing-momentum that is equal to the mean value of the data.

question/concern: removing one nucleon from 2N SRC does not destroy interactions of second nucleon of SRC with mean field - ***should suppress emission from pairs with high momenta of the pair. Effects of f.s.i.?***

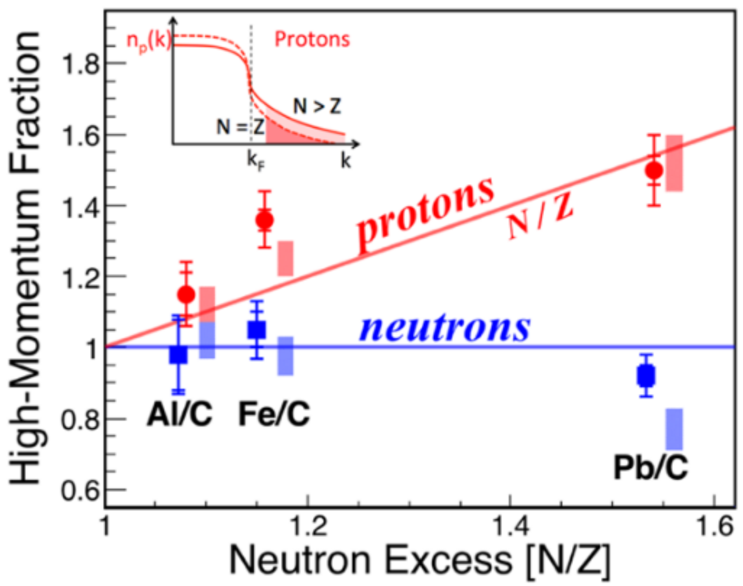
Example: for 12 C absorption for proton knockout is nearly a factor of 1.4 different for p and s-shells. (Zhalov 90).

Many impressive experimental results in the last few years. Perhaps most impressive

pn dominance is tested in both kinematics when neutron / proton is spectator and proton is knocked out, and in when proton is spectator and neutron is knocked out + restoration of Wigner symmetry at large momenta

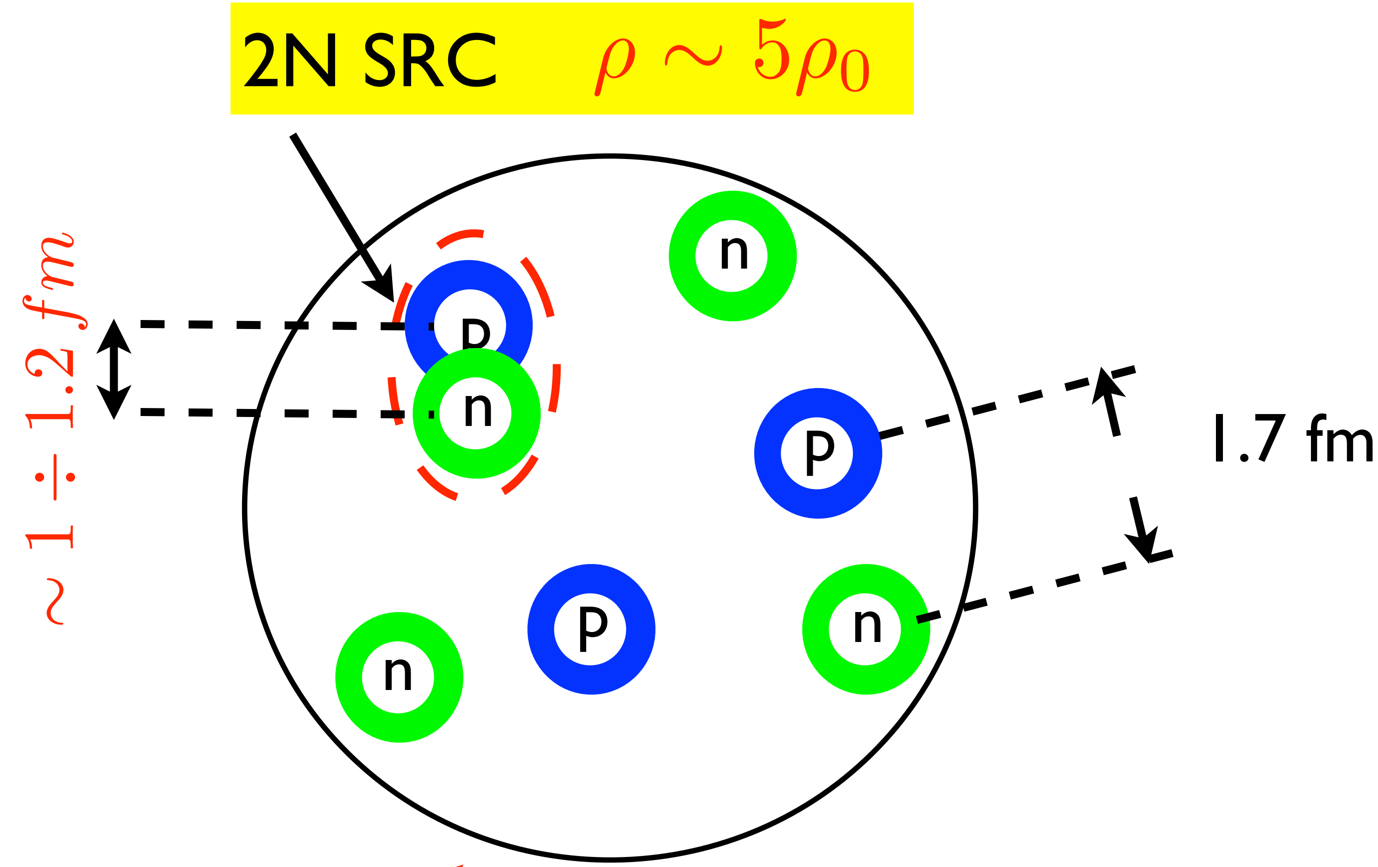
if all NN pairs are I=0, # of high momentum protons = # of high momentum neutrons

prediction (M.Sargsian)



Extracted fraction of high-momentum ($k>k_F$) protons and neutrons in neutron rich nuclei relative to Carbon. In lead 30% of protons are above Fermi surface, and 20% neutrons.
In neutron stars for $\rho=2\rho_0$ most of the protons have momenta > $k_F(\rho_0)$

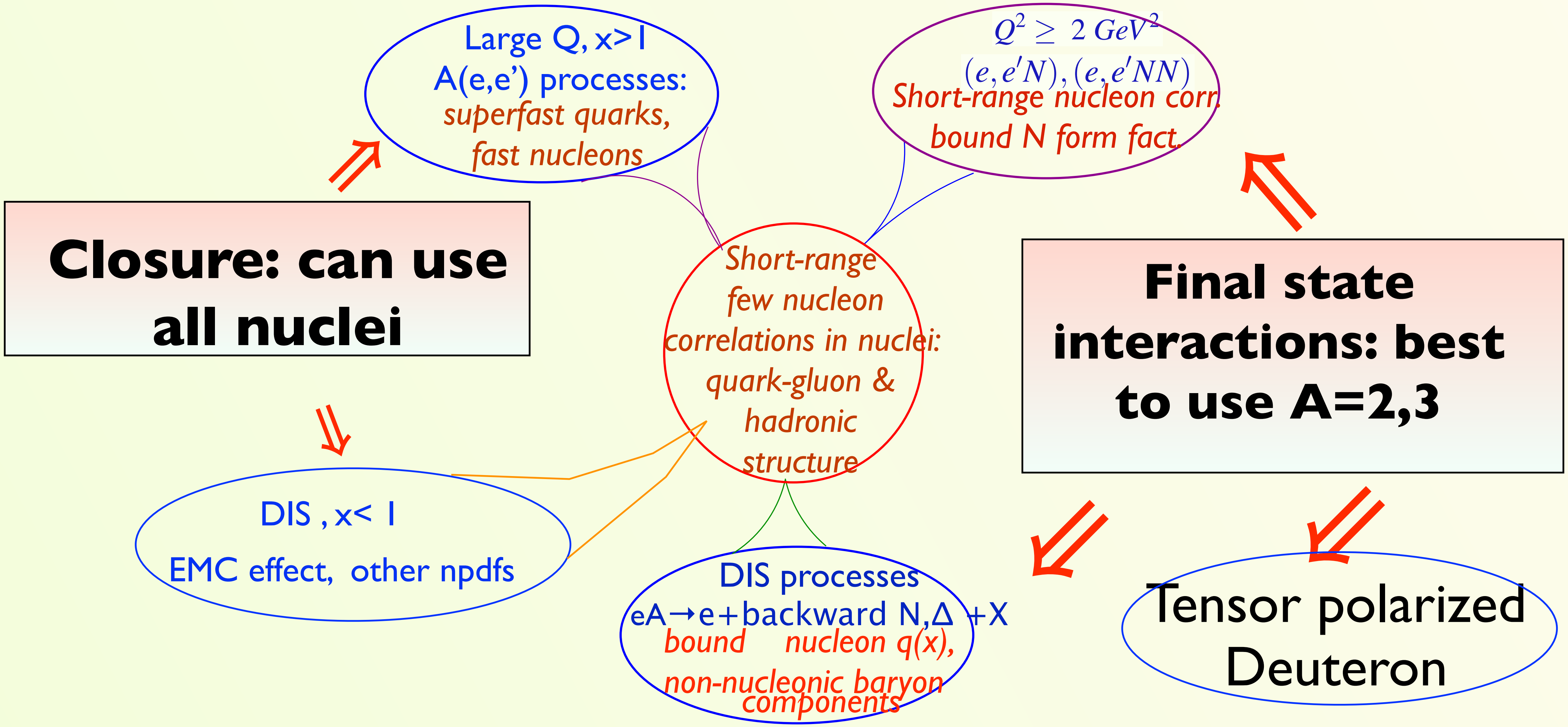
Short-range NN correlations (SRC) have densities comparable to the density in the center of a nucleon - *drops of cold dense nuclear matter*



Connections to physics of neutron stars:
a) I=1 nn correlations,
b) admixture of protons in neutron stars → I=0 sensitivity
c) multi-nucleon correlations

for density $2\rho_0$: protons surrounded by neutrons with density $4\rho_0$ — comparable to local density in SRC

Multi prong approach to the study of SRC and their inner structure started to emerge



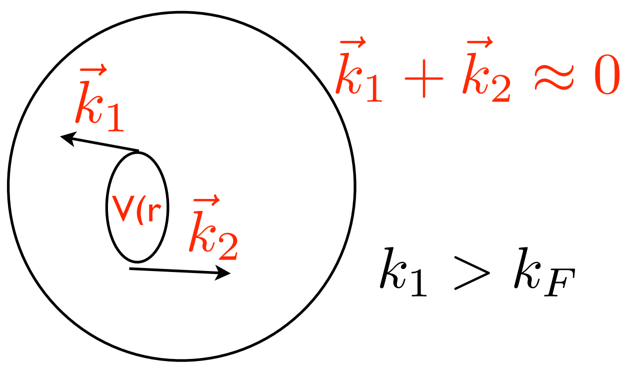
Package deal - cannot cherry pick some of the processes - would result in a gross loss of information

Important to have complementary studies of large angle hadron/photon induced exclusive reactions: γ A→ π N (A-1) with A-1 decay; (anti) proton

Hard exclusive processes where a nucleon of SRC is removed instantaneously

probe another quantity sensitive to SRC - nuclear decay function (FS 77-88) - probability to emit a nucleon with momentum k_2 after removal of a fast nucleon with momentum k_1, leading to a state with excitation energy E_r (nonrelativistic formulation)

$$D_A(k_2, k_1, E_r) = |\langle \phi_{A-1}(k_2, ...)\,|\delta(H_{A-1} - E_r)a(k_1)|\,\psi_A\rangle|^2$$



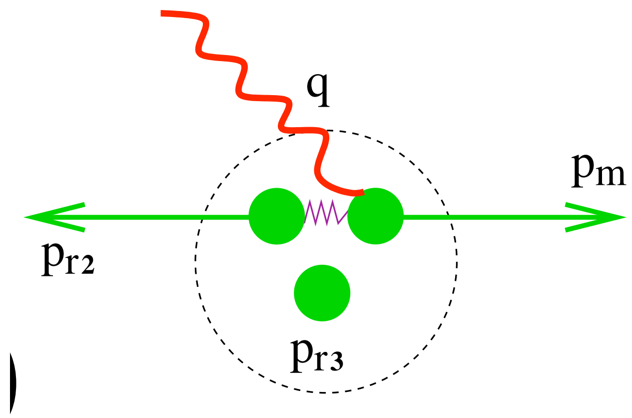
General principle (LF&MS77): to release a nucleon of a SRC - need to remove nucleons from the same correlation - perform a work against potential $V_{12}(r)$

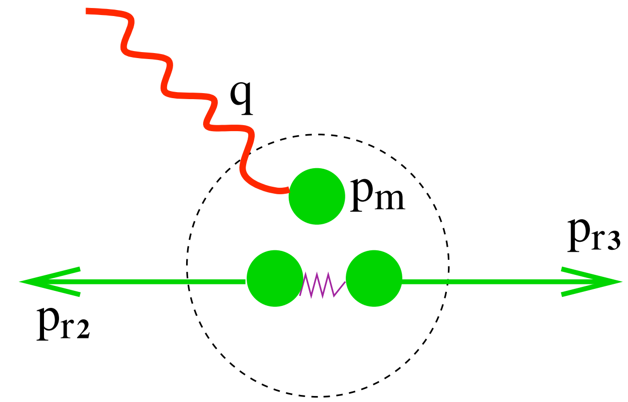
Operational definition of the SRC: nucleon belongs to SRC if its instantaneous removal from the nucleus leads to emission of one or two nucleons which balance its momentum: includes not only repulsive core but also tensor force interactions.

For 2N SRC can model decay function as decay of a NN pair moving in mean field (like for spectral function in Ciofi & Simula, LF&MS 01)

Piasetzky et al 06

Spectator is released





Emission of fast nucleons "2" and "3" is strongly suppressed due to FSI

resembles 2N momentum distribution

does not resemble 2N momentum distribution

Studies of the spectral and decay function of 3He reveal both 2N and 3N SRCs

Sargsian et al 2004

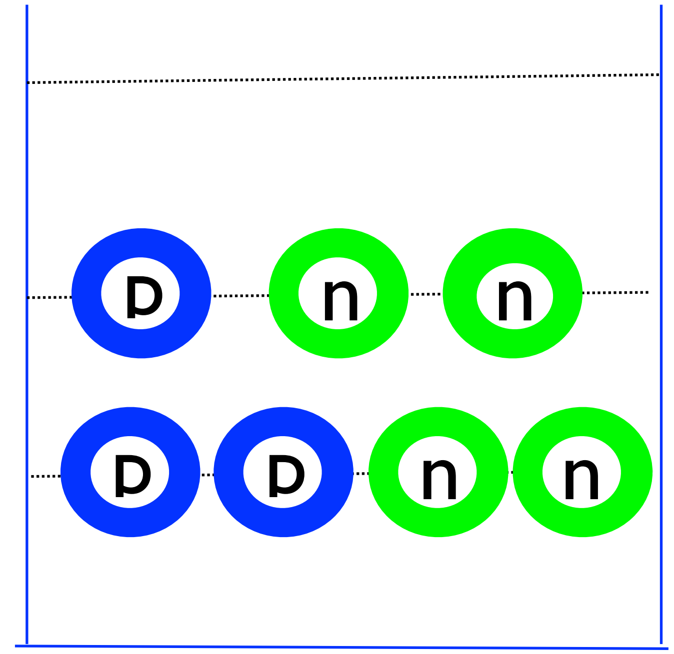
Note that in the decay one needs to take into account recoil effects - naturally accounted for when using relativistic light-cone decay functions: conservation of LC fractions

Problem - no methods so far to calculate decay functions for A >4. However the decay function and another interesting characteristics of the nuclear structure - two nucleon momentum distributions in the nuclei is close for $k_1+k_2=0$, $k_1>>k_F$ *though not if* $|k_1+k_2|>$ 50 - 100 MeV/c.

The prediction of back - to - back correlation differs from the expectations based on the textbook picture of nuclei:

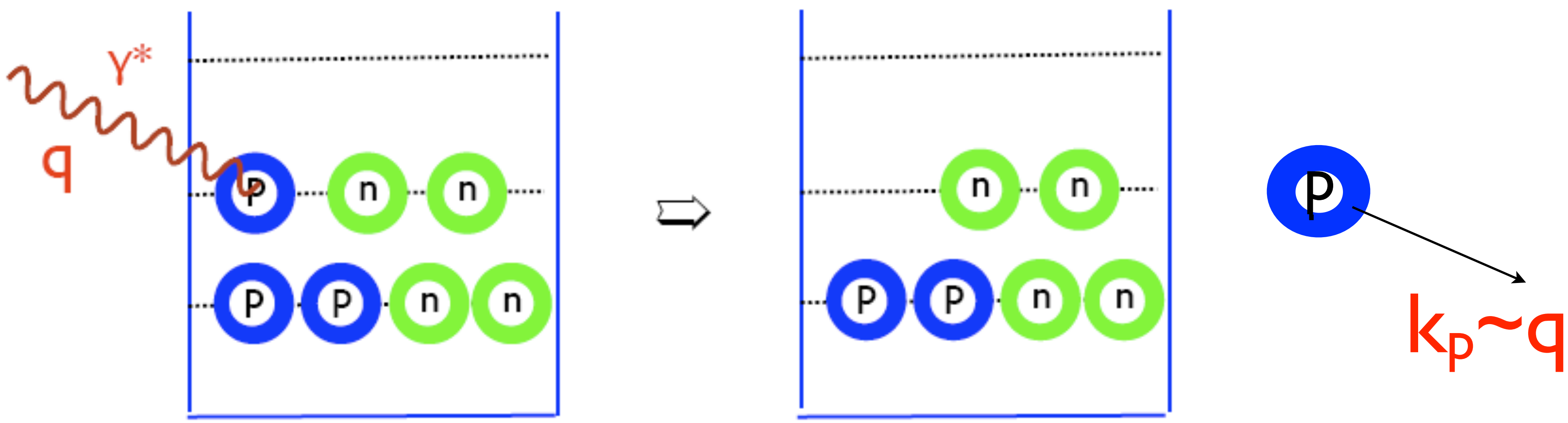
p-level

s-level



Nucleons occupy the lowest levels given by the shell model

What happens if a nucleon is removed from the nucleus?



removal of a nucleon

Residual nucleus in ground or excited state of the shell model Hamiltonian - decay product practically do not remember direction of momentum of struck proton.

Last decade a qualitative progress in the study of SRC based on the analysis of the high momentum transfer data:

(p,2pn) BNL

(e,e’), (e,e’p), (e,e’n) (e,e’pp) & (e,e’pn) JLAB

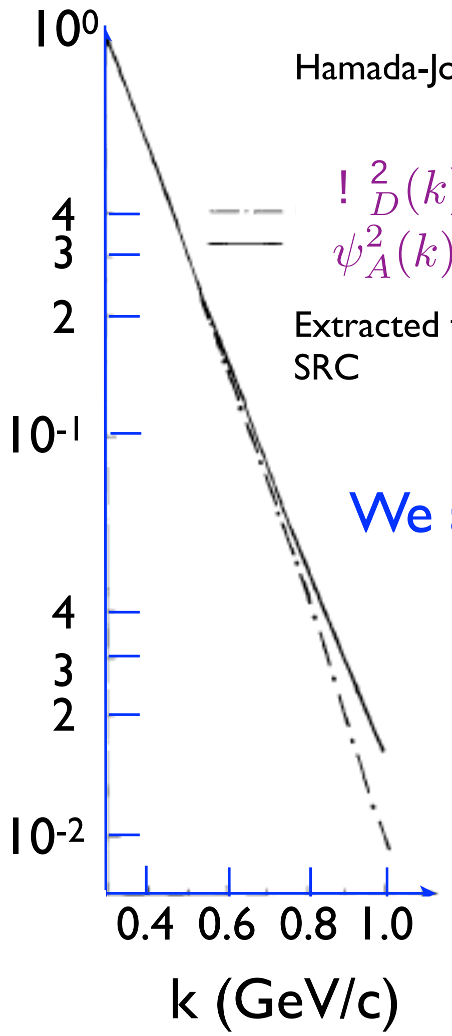
SRC are not anymore an elusive property of nuclei !!

The findings confirm our predictions based on the study of the structure of SRC in nuclei (77-93), add new information about isotopic structure of SRC. In particular this confirms our interpretation of the fast backward hadron emission observed in the 70’s-80’s as to due to SRC

Exploring SRC via study of the decay function

First application of the logic of decay function - spectator mechanism of production of fast backward nucleons - observed in high energy proton, pion , photon - nucleus interactions with a number of simple regularities. We suggested - spectator mechanism - breaking of 2N, 3N SRCs. We extracted (Phys.Lett 1977) two nucleon correlation function from analysis of
$\gamma(p)\ ^{12}C \to$ backward $p+X$ processes [no backward nucleons are produced in the scattering off free protons!!!]

Spectator production of the backward proton from 2N SRC

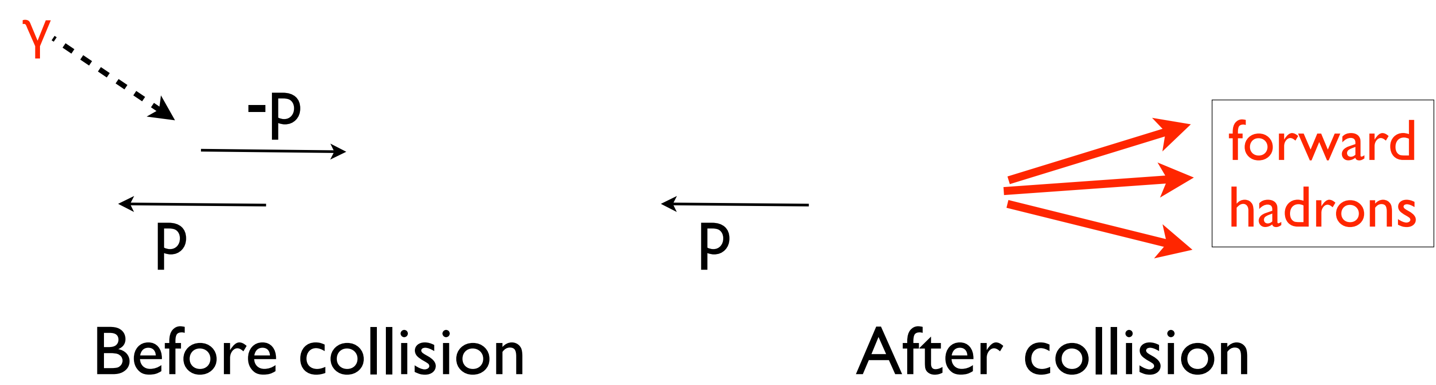


Hamada-Johnston WF

$!^{2}_{D}(k)/!^{2}_{D}(k = 300MeV/c)$

$\psi^2_A(k)/\psi^2_A(k = 300MeV/c)$

Extracted from the data assuming dominance of 2N SRC



We also estimated $a_2(^{12}C) = 4 \div 5$

confirmed by (e,e') x> 1 data

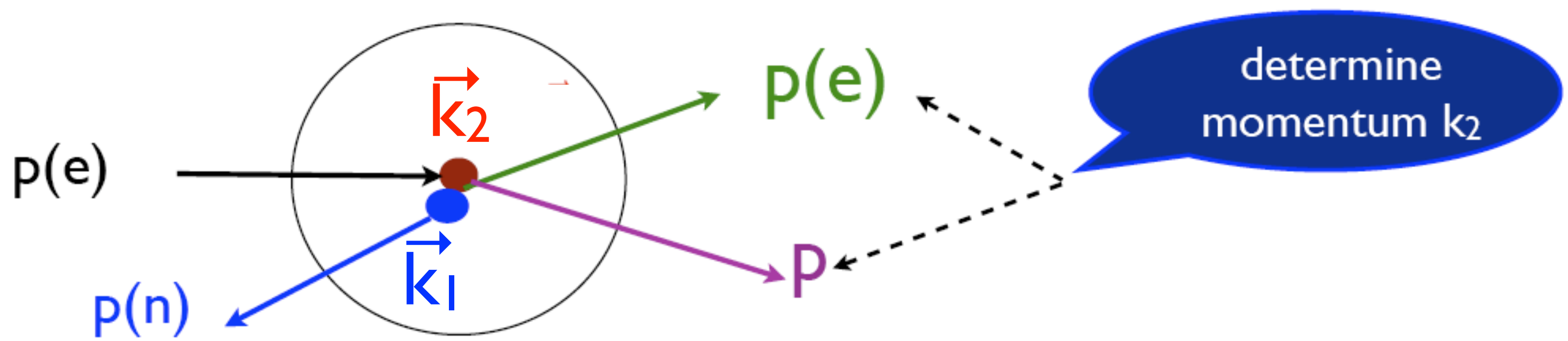
Momentum distributions normalized to its value at 300 MeV/c.

We were prompted by G. Farrar in 86 to discuss large angle pp scattering off the bound nucleon: p + A → pp (A-1)* - prime topic was color transparency. Next we realized that this process selects scattering off the fast forward moving protons since elastic pp cross section

$$\frac{d\sigma}{d\theta_{c.m.}} = \frac{1}{s^{10}} f(\theta_{c.m.})$$

Hence in a large fraction of the events there should be fast neutrons flying backward. We heard of plans of a new experiment - EVA. So without much hope that somebody would notice we wrote that it would be nice to have a backward neutron detector added to EVA. Eli Piasetzky (Tel Aviv Uni) did notice!!!
He probably did not know that it is impossible to measure SRCs !!!

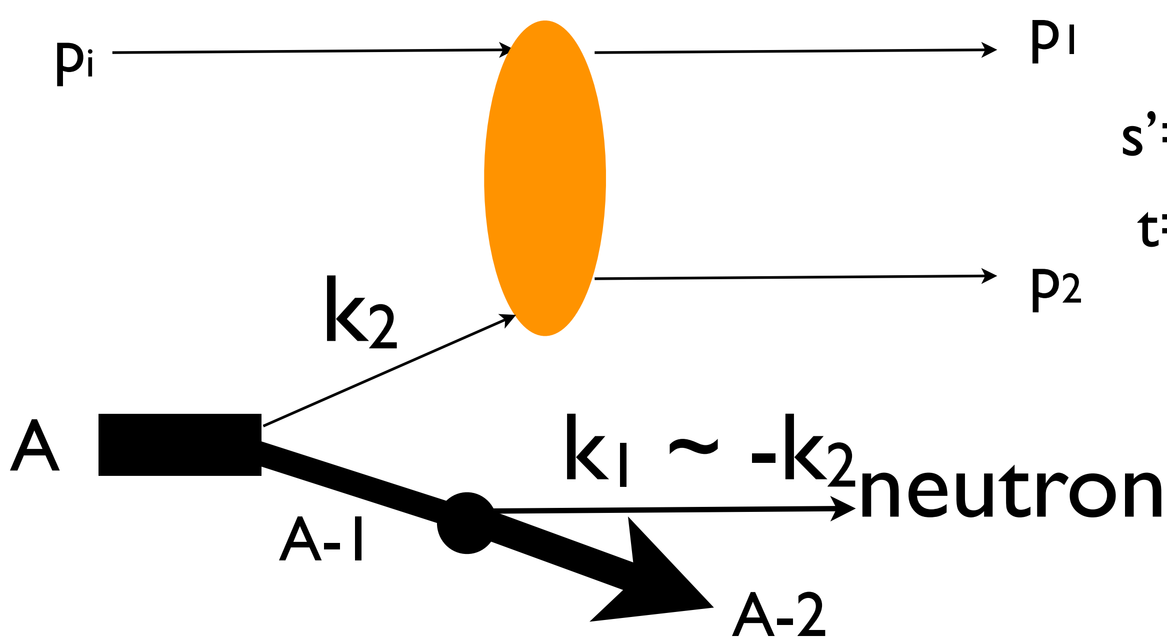
To observe SRC directly it is far better to consider semi-exclusive processes
e(p) +A → e(p) + p + " nucleon from decay" +(A-2) since it measures
both momentum of struck nucleon and decay of the nucleus



Two novel experiments reported results 2006- 2010

- *EVA BNL 5.9 GeV protons (p,2p)n* $-t = 5\ GeV^2;\ t=(p_{in}-p_{fin})^2$

- *(e,e' pp), (e,e'pn) Jlab* $Q^2 = 2GeV^2$



$s' = (p_1 + p_2)^2$

$t = (p_1 - p_p)^2$

$k_2 = p_1 + p_2 - p_i$

Collider frame

$s' = \alpha s_{NN}, \ \alpha < 1$

neutron momentum $(2-\alpha)p$

From measurement of p_1, p_2 $p_{neutron}$ choose small excitation energy of A-2 (< 100 MeV)

$\sigma = d\,\sigma^{pp \to pp}/dt(s',t)$ * (Decay function)

Test of Factorization: $\sigma / d\,\sigma^{pp \to pp}/dt(s',t)$ independent of s', t

Analysis of BNL E850 data $pC \to ppn + (A-2)^*$

at energy and momentum transfer ≥ 3 GeV

Evidence for the Strong Dominance of Proton-Neutron Correlations in Nuclei

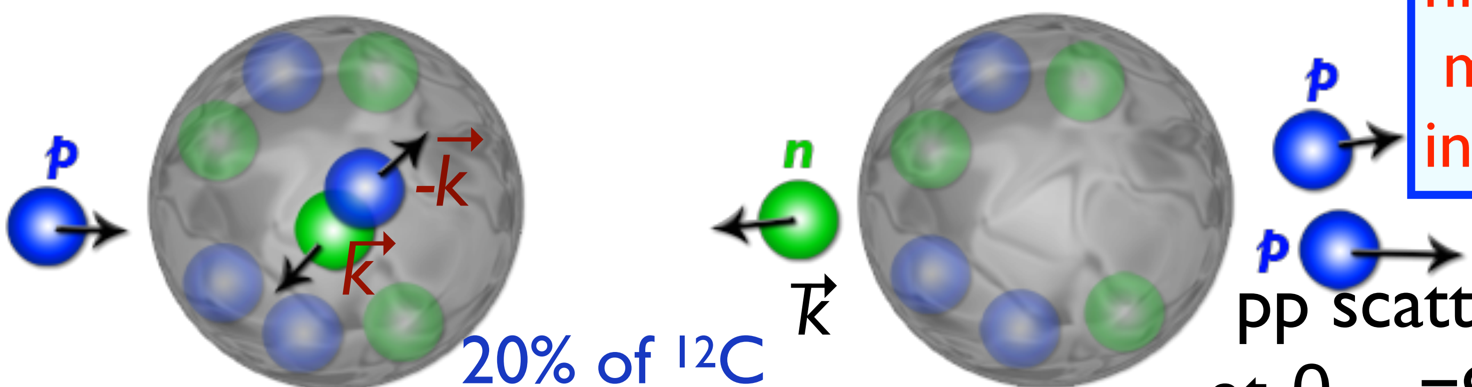
E. Piasetzky,[1] M. Sargsian,[2] L. Frankfurt,[1] M. Strikman,[3] and J. W. Watson[4]

PRL 06

Analysis using decay function modeled using 2N correlation model (including relativistic effects) - the same approximation as for spectral function in CSFS 91

spectator mechanism of backward nucleon production *FS77*

Probability to emit neutron is amazingly high ~90% after we accounted for the motion of the pair (measured/calculated independently) and detector acceptance



20% of ^{12}C wave function

pp scatter at $\theta_{c.m.}=90^{\circ}$

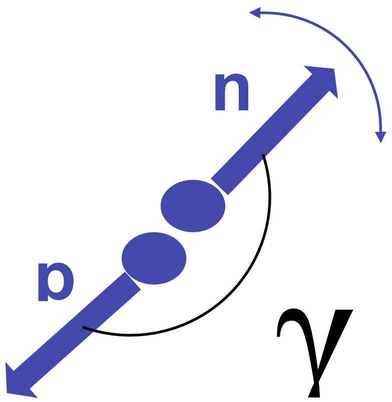
pn/pp > 16; I=0 dominance - qualitatively consistent with current calculations of nuclear wave functions

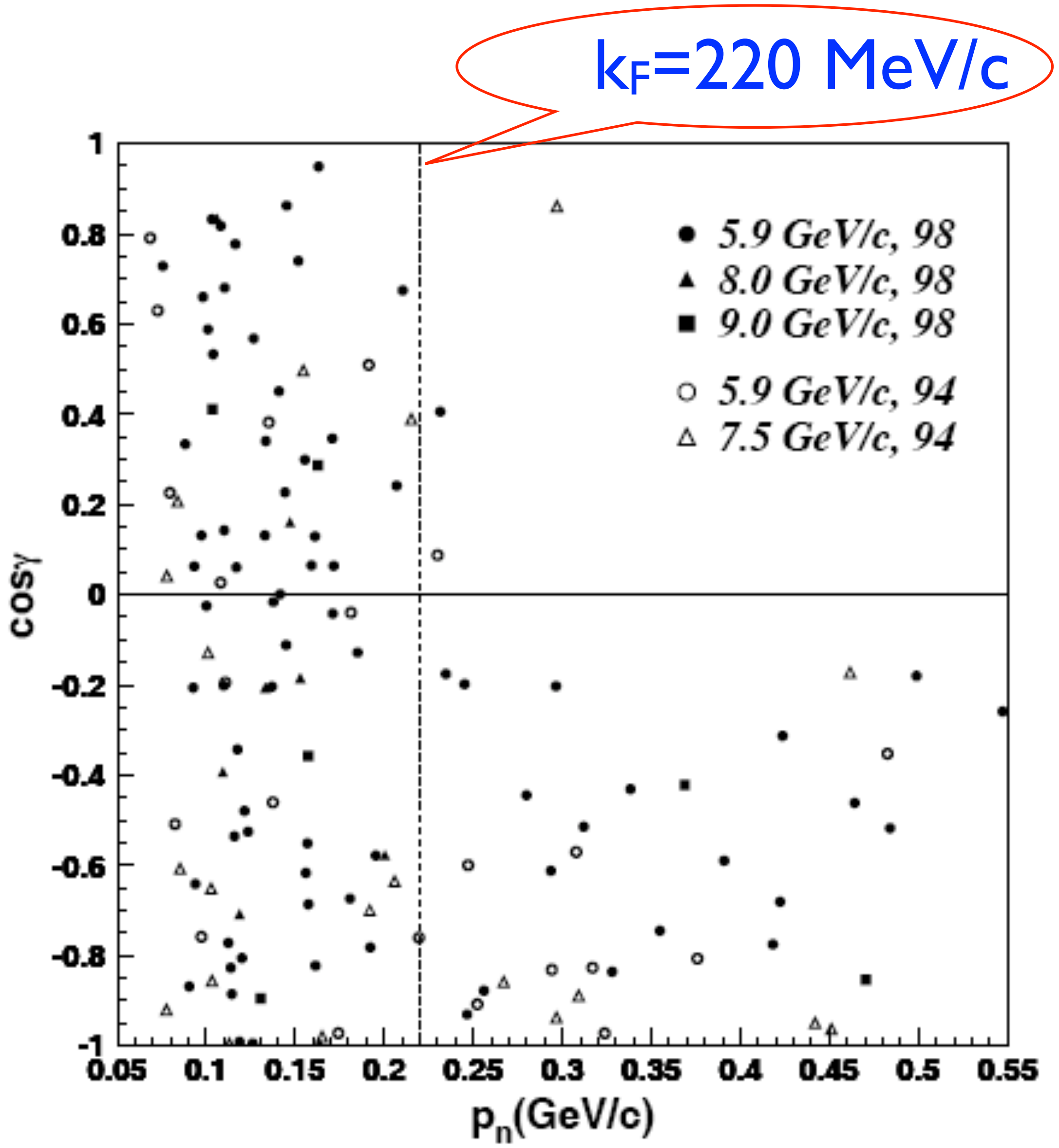
Before collision

After collision

removal of a proton with momentum > 250 MeV/c

~90% probability of emission of neutron with similar but opposite momentum

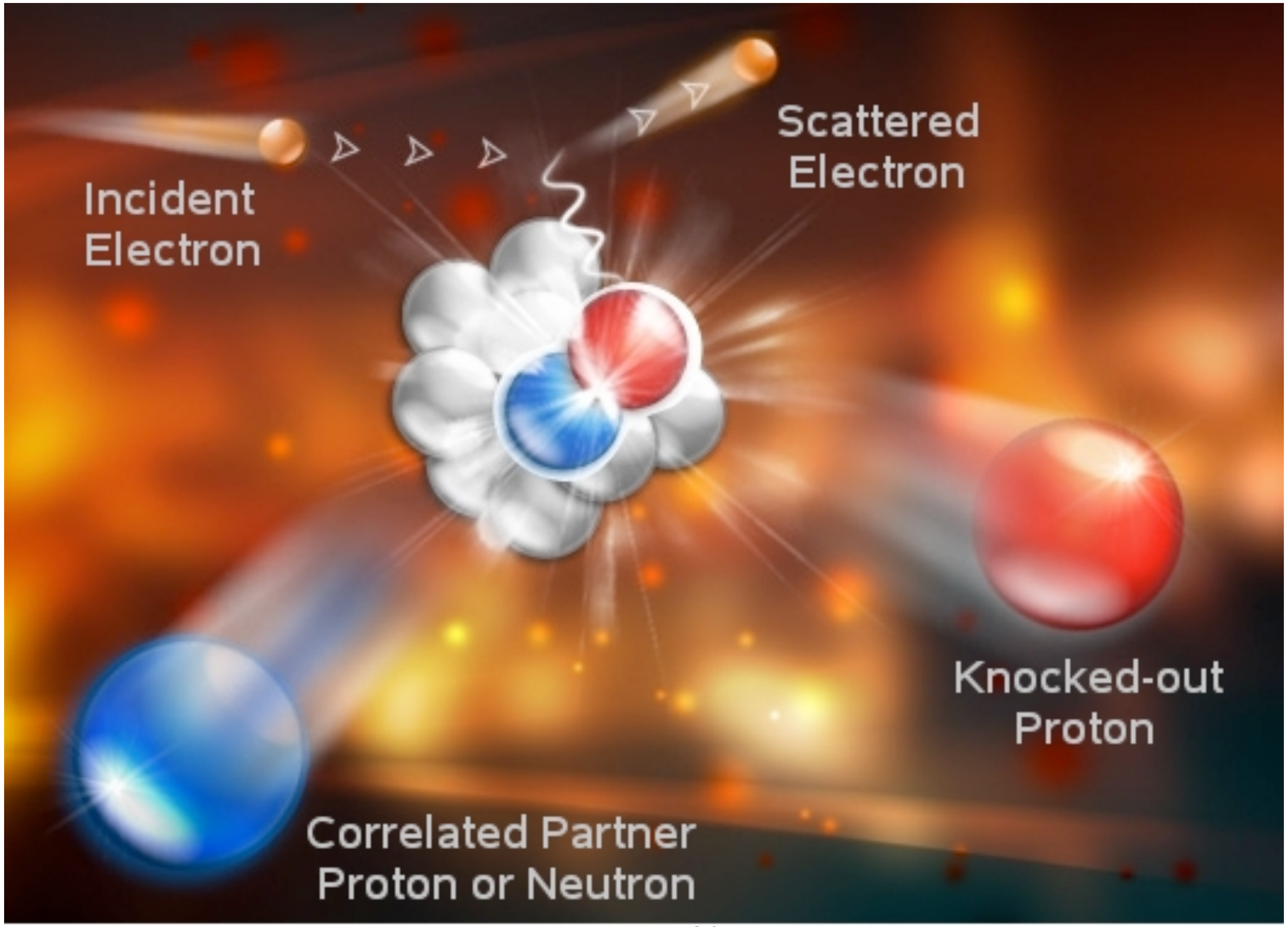




BNL Carbon data of 94-98. The correlation between p_n and its direction γ relative to p_i. The momenta on the labels are the beam momenta. The dotted vertical line corresponds to k_F=220 MeV/c.

SRC appear to dominate at momenta k> 250 MeV/c - very close to k_F. *A bit of surprise* - we expected dominance for k> 300 - 350 MeV/c. Naive inspection of the realistic model predictions for $n_A(k)$ clearly shows dominance only for k > 350 MeV/c. Important to check a.s.p. - Can be done at lower momentum transfer than at $k \gg k_F$

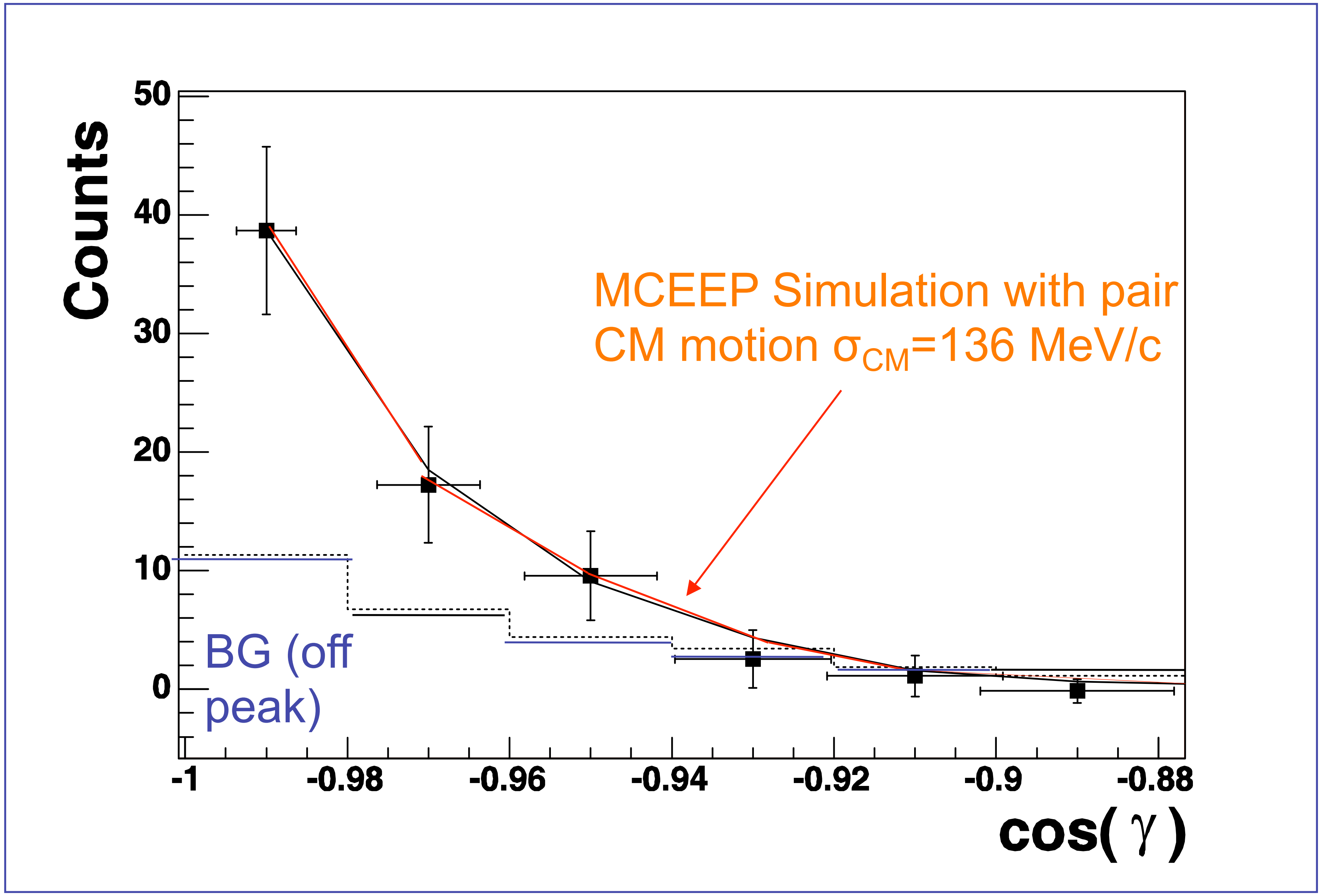
Jlab: from study of (e,e'pp), (e,e'pn)~10% probability of proton emission, strong enhancement of pn vs pp. The rate of pn coincidences is similar to the one inferred from the BNL data

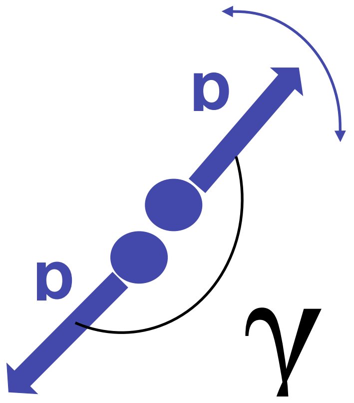


T-shirt of Jlab 09

Directional correlation

$^{12}C(e,e'pp)$

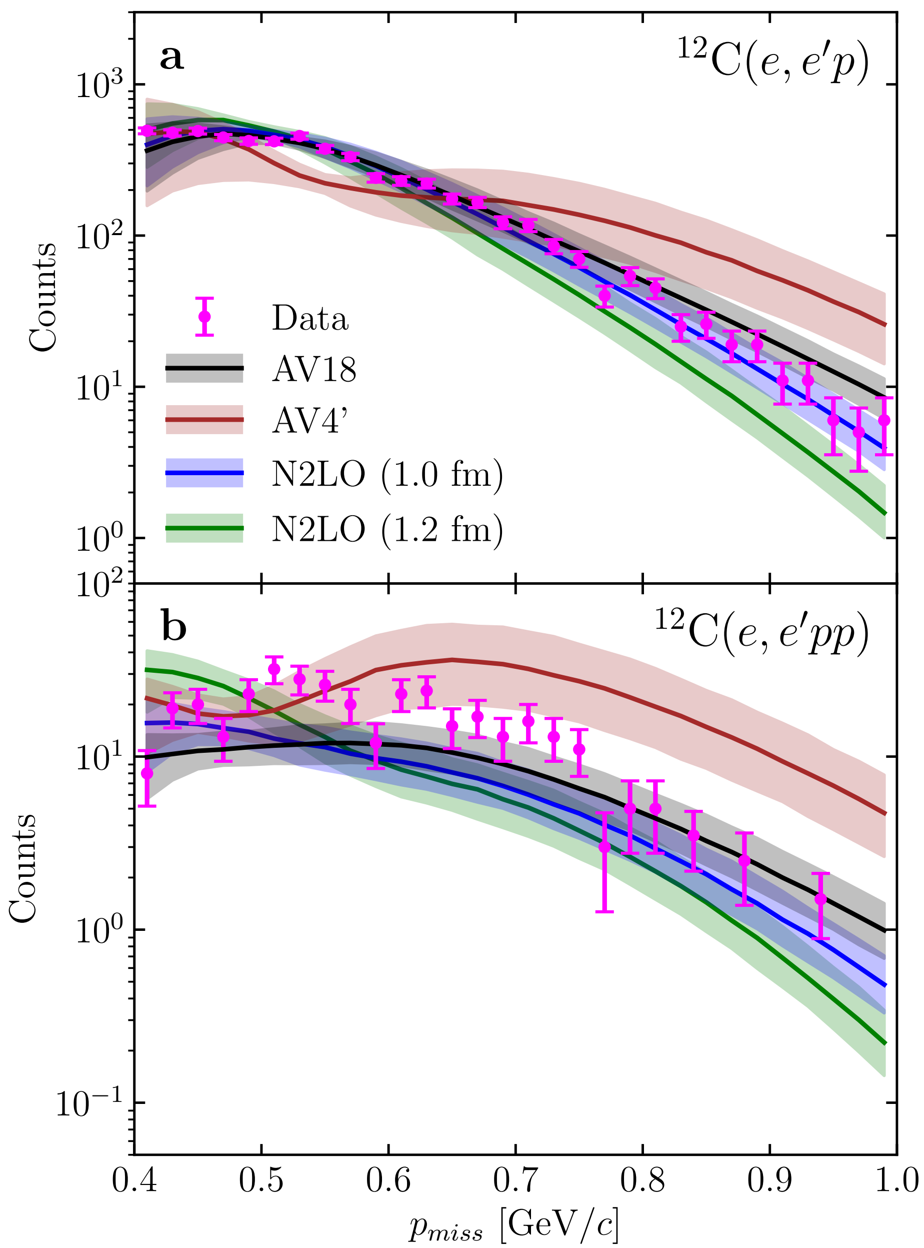




From (e,e'N), (e,e'NN) data consistent picture of scattering off pn and pp correlations

Push to high nucleon momenta - relativistic effects have to be addressed (Nature2020)

Th same data I shown before ffor spectral function

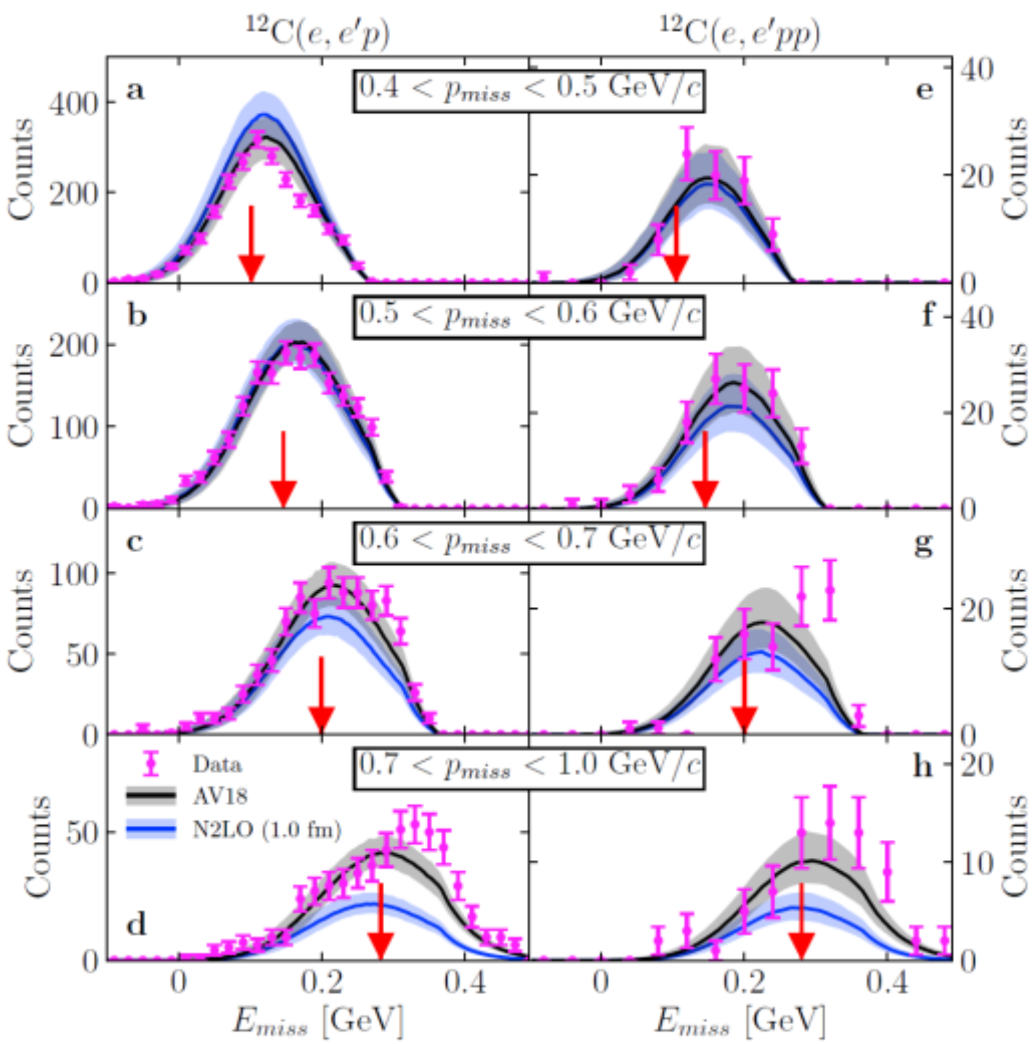


Relativistic effects treated using light cone dynamics (FS 81) in missing momentum dependence taking into account nonlinear relation between observed p_{miss} and momentum in the wave function which depends on the emission angle. Several realistic (and unrealistic - AV 4') wave functions are used.

No time to discuss the reasons why LC is necessary for high energies except to say that the reasons are similar to introduction of parton densities in parton model and in QCD

Testing spectral function

Nature

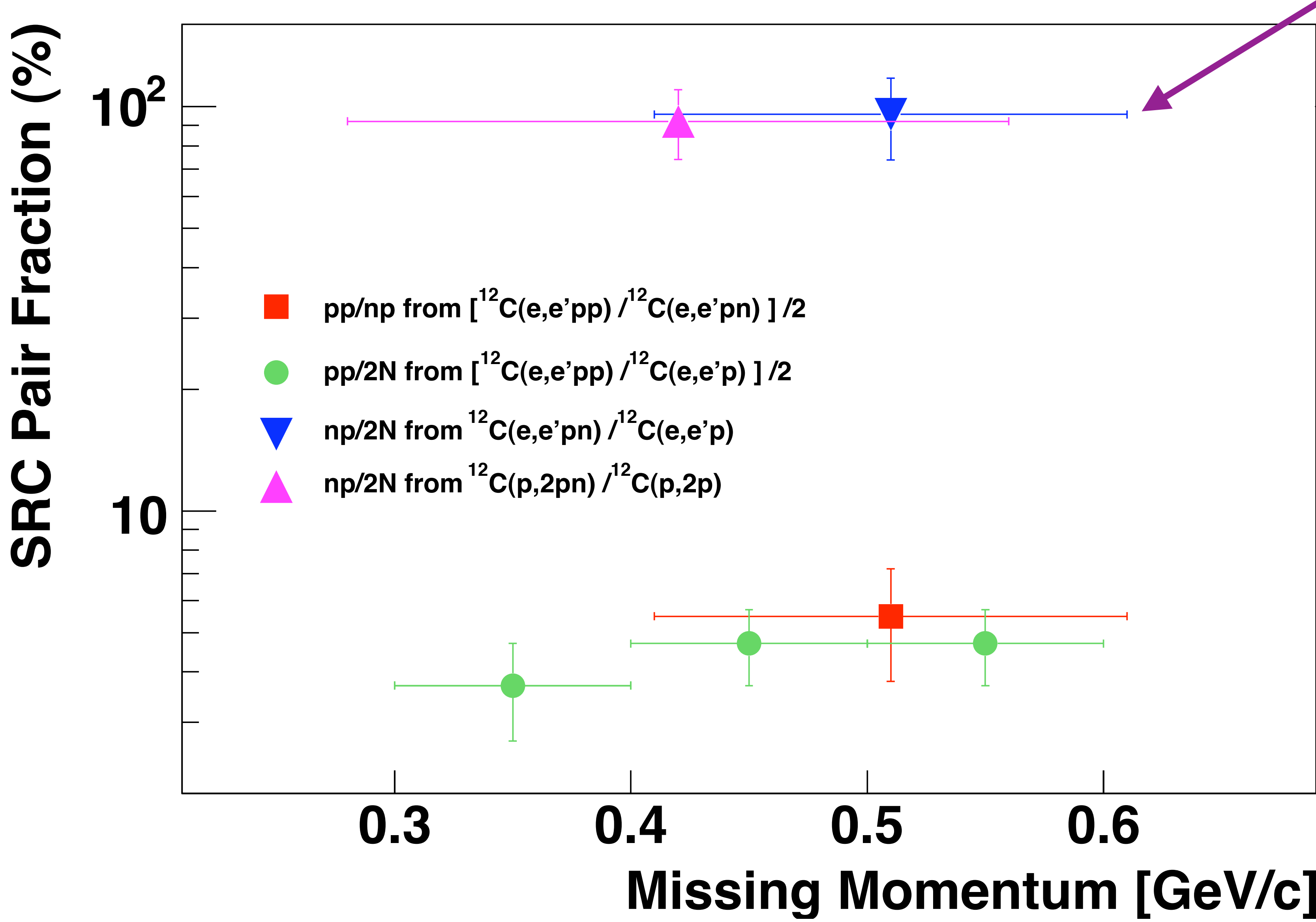


Data mining. Group with participation of a few theorists

E_{miss} dependence of the ^{12}C(e,e′p) (left) and ^{12}C(e,e′pp) (right) reactions for different p_{miss} values. The red arrow indicates the expected E_{miss} for a breakup of SRC pair with p_{CM}=0 and a missing-momentum that is equal to the mean value of the data.

question/concern: removing one nucleon from 2N SRC does not destroy interactions of second nucleon of SRC with mean field - ***should suppress emission from pairs with high momenta of the pair. Effects of f.s.i.?***

Example: for 12 C absorption for proton knockout is nearly a factor of 1.4 different for p and s-shells. (Zhalov 90).



Note - BNL and Jlab studied very different kinematics for breakup of 2N SRC - similarity of the numbers is highly non-trivial

Our analysis of BNL Experiment measurement was 92^{+8}_{-1} %

accounting for charge exchange

$$\frac{np-SRC}{pp-SRC} = 18 \pm 5$$

In Carbon 12

Summary of the theoretical analysis of the experimental findings

practically all of which were predicted well before the data were obtained

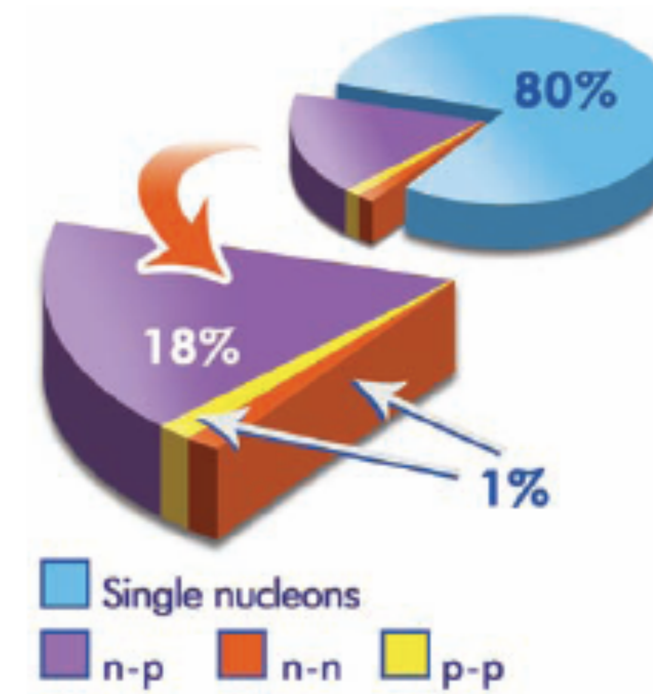
More than ~90% all nucleons with momenta $k \geq 300$ MeV/c belong to two nucleon SRC correlations

Probability for a given proton with momenta $600 > k > 300$ MeV/c belong to **pn** correlation is ~ 20 times larger than for **pp** correlation

Probability for a nucleon to have momentum > 300 MeV/c in medium nuclei is ~20%

Probability of non-nucleonic components within SRC is small < 20% - 2N SRC mostly build of two nucleons not 6q, ΔΔ,...

Three nucleon SRC are present in nuclei with a significant probability



The average fraction of nucleons in the various initial-state configurations of ^{12}C.

The findings confirm our predictions based on the study of the structure of SRC in nuclei (77-93), add new information about isotopic structure of SRC. In particular this confirms our interpretation of the fast backward hadron emission observed in the 70's-80's as to due to SRC

Near future

A(e,e’p) from data mining, many channels from Jlab 12

(p, pN) experiment at GSI

Dubna (carbon 12 beam, and at some point polarized deuteron)

FAIR? J-PARC ?

Challenges - more detailed treatment of fsi & relativistic effects, absolute cross sections, tests of factorization proton vs electron beams.

Next step - going beyond 2 N SRC approximation: 3N SRC,

Conclusions

Last decade - impressive progress in understanding SRC in nuclei

Next few years: tagged structure functions in eD to test critically the origin of the EMC effect , probing ultra high momenta in nuclei, three nucleon correlations, determining optimal formalism for description relativistic dynamics

an elephant in a porcelain shop: nonnucleonic degrees of freedom.

Δ-isobars: ~ few % in models which treat isobars explicitly, comparable to NN SRC at large momenta

Quark - gluon degrees of freedom - EMC effect

EMC effect and related phenomena

Let us imagine that one would know all features of SRC we know now and would be asked - how large nuclear effects are expected for DIS for deviation of

$R_A(x,Q^2) = 2F_{2A}(x,Q^2)/AF_{2D}(x,Q^2)$ from one

Exotics - one when nucleons are close: SRC P=20% + (P'> 80%) SRC in 2N configuration.

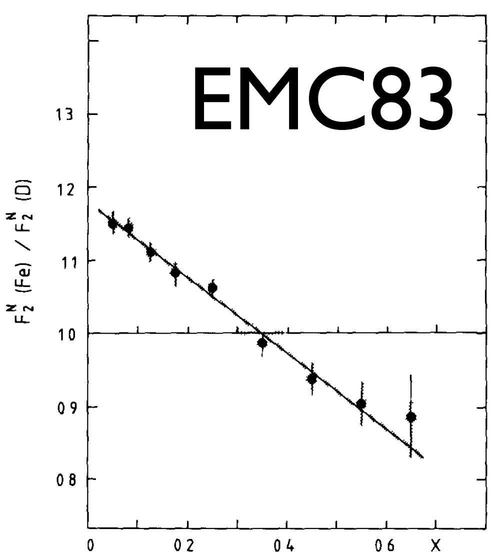
→ P x (1- P') ~ 4 % effect and Fermi motion effect is < 2% for x <0.6 (discussion below)

Major discovery (by chance) - the European Muon Collaboration effect - substantial difference of quark Bjorken x distributions at x > 0.25 in A>2 and A=2 nuclei: a large (15%) deviation of the EMC ratio from 1

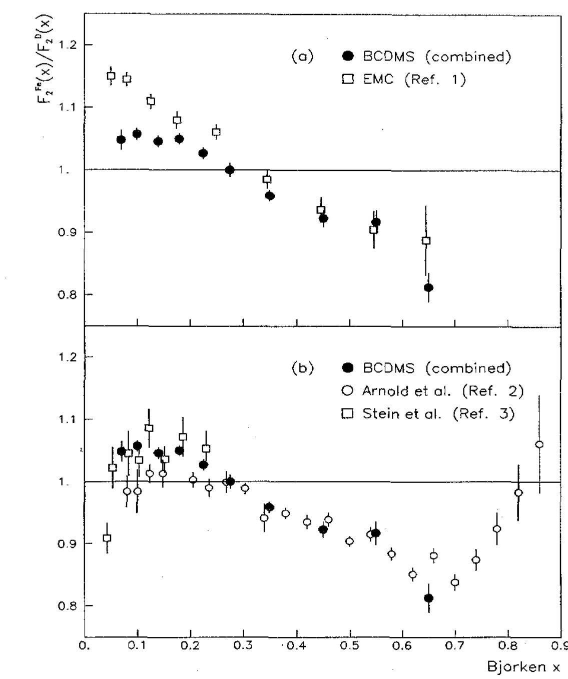
$R_A(x,Q^2) = 2F_{2A}(x,Q^2)/AF_{2D}(x,Q^2)$ from one

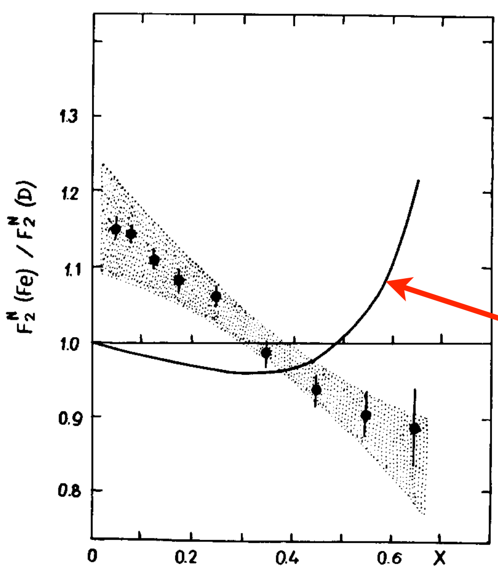
$$q_\nu = (q_0, \vec{q}), x = x_{Bj} = -q^2/2q_0 m_p \qquad q_\nu = p_{\gamma^*}$$

straight line fit - suggested universal mechanism. Fermi motion very small effect with R(x>0.5) >1



1987 - effect is significantly





Theoretical expectation under assumption that nucleus consists only of nucleons FS 81

Bjorken scaling within 30% accuracy - caveat - HT effects are large in SLAC kinematics for x≥ 0.5. Even more so at Jlab energies

Can account of Fermi motion describe the EMC effect?

YES

If one violates exact QCD sum rules of baryon charge conservation or momentum conservation or both

Many nucleon approximation:

$$F_{2A}(x,Q^2) = \int \rho_A^N(\alpha, p_t) F_{2N}(x/\alpha) \frac{d\alpha}{\alpha} d^2 p_t$$

Light cone nuclear nucleon density (light cone projection of the nuclear spectral function

≡probability to find a nucleon having momentum αP_A

$$\int \rho_A^N(\alpha, p_t) \frac{d\alpha}{\alpha} d^2 p_t = A$$

baryon charge sum rule

$$\frac{1}{A} \int \alpha \rho_A^N(\alpha, p_t) \frac{d\alpha}{\alpha} d^2 p_t = 1 - \lambda_A$$

fraction of nucleus momentum NOT carried by nucleons

In nucleus rest frame $x = AQ^2/2m_A q_0$

Since spread in α due to Fermi motion is modest ⇒

do Taylor series expansion in (1- α): α= 1+ (α-1)

Fermi motion

$$R_A(x,Q^2) = 1 - \frac{\lambda_A x F_N'(x,Q^2)}{F_N(x,Q^2)} + \frac{x F_{2N}'(x,Q^2) + (x^2/2) F_{2N}''(x,Q^2)}{F_{2N}(x,Q^2)} \cdot \frac{2(T_A - T_{^2H})}{3m_N}$$

$$F_{2N} \propto (1-x)^n, n \approx 3 \qquad R_A(x,Q^2) = 1 - \frac{\lambda_A n x}{1-x} + \frac{xn\left[x(n+1)-2\right]}{(1-x)^2} \cdot \frac{(T_A - T_{^2H})}{3m_N}$$

n=3

R-1 small negative for x <0.5
R-1 > 0 and rapidly growing for x >0.5

Jlab - due to HT effects n~ 2. Crossover x=0.66

EMC effect is unambiguous evidence for presence of non nucleonic degrees of freedom in nuclei. The question - what are they?

O.Nash: God in his wisdom made a fly
But he forget to tell us why

Why one has to use light-cone densities: DIS develops along the LC sampling the LC slice of the wave function

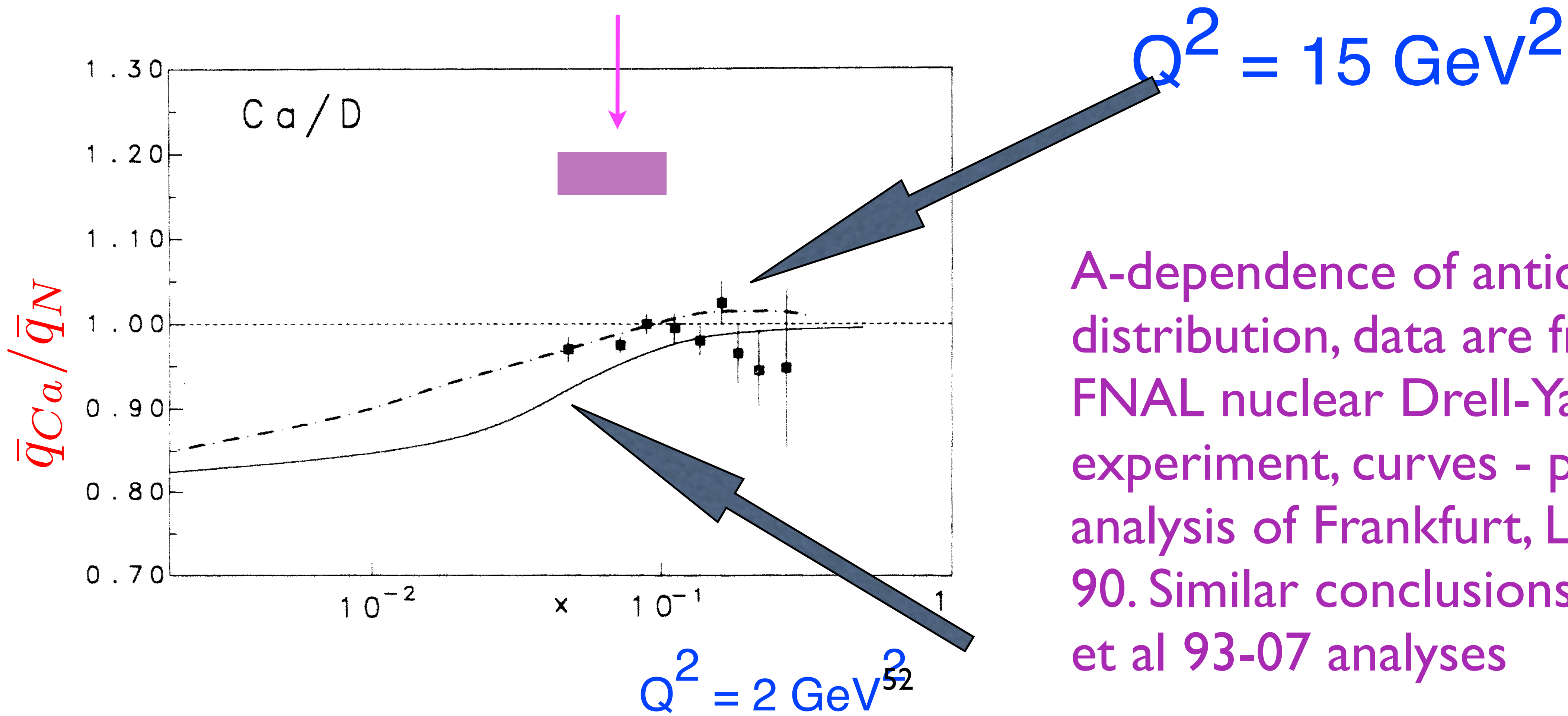
Weinberg has been first (1966) to elucidate the advantages of the infinite momentum frame/ light cone wave functions for the description of bound states. He writes: "The Feynman rules provide a perturbation theory in which the Lorentz invariance of the S matrix is kept visible at every step. However this is accomplished only at the cost of manifest unitarity, by lumping together intermediate states with different numbers of particles and antiparticles. Thus when we try to sum Feynman diagrams to obtain integral equations like the Bethe—Salpeter equation it proves very difficult to justify the omission of any particular diagrams since there is no one-to-one relation between internal lines and intermediate states."

As a result it is very difficult to implement conservation laws using fixed number of degrees of freedom starting from a vertex function, or fixed time (nonrelativistic) description of nuclei

Drell-Yan experiments: $\bar{q}_{Ca}/\bar{q}_N \approx 0.97$ vs prediction of meson model

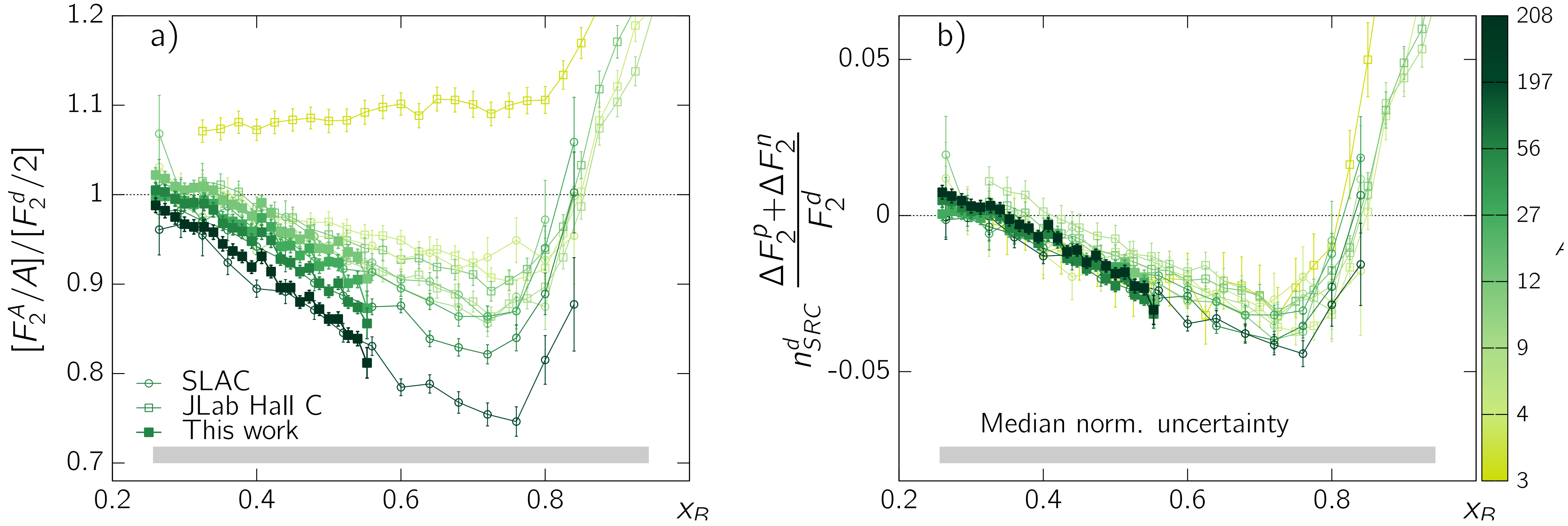
1989

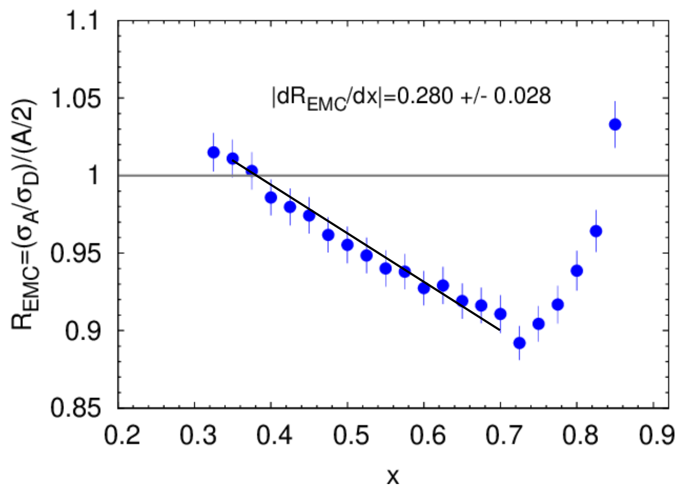
$\bar{q}_{Ca}(x)/\bar{q}_N = 1.1 \div 1.2_{|\, x=0.05 \div 0.1}$



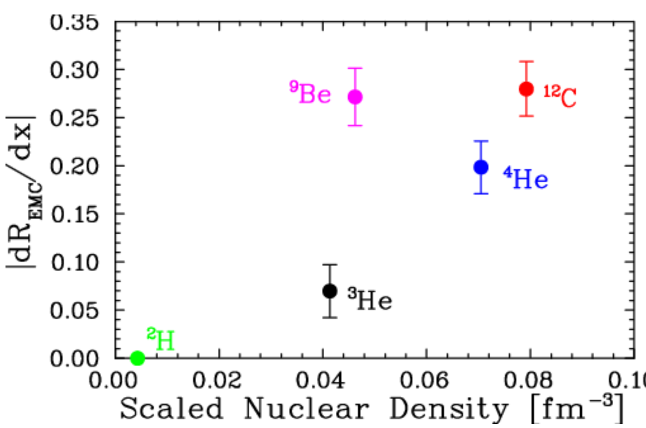
A-dependence of antiquark distribution, data are from FNAL nuclear Drell-Yan experiment, curves - pQCD analysis of Frankfurt, Liuti, MS 90. Similar conclusions Eskola et al 93-07 analyses

Approximate universality of the x-dependence of the EMC effect

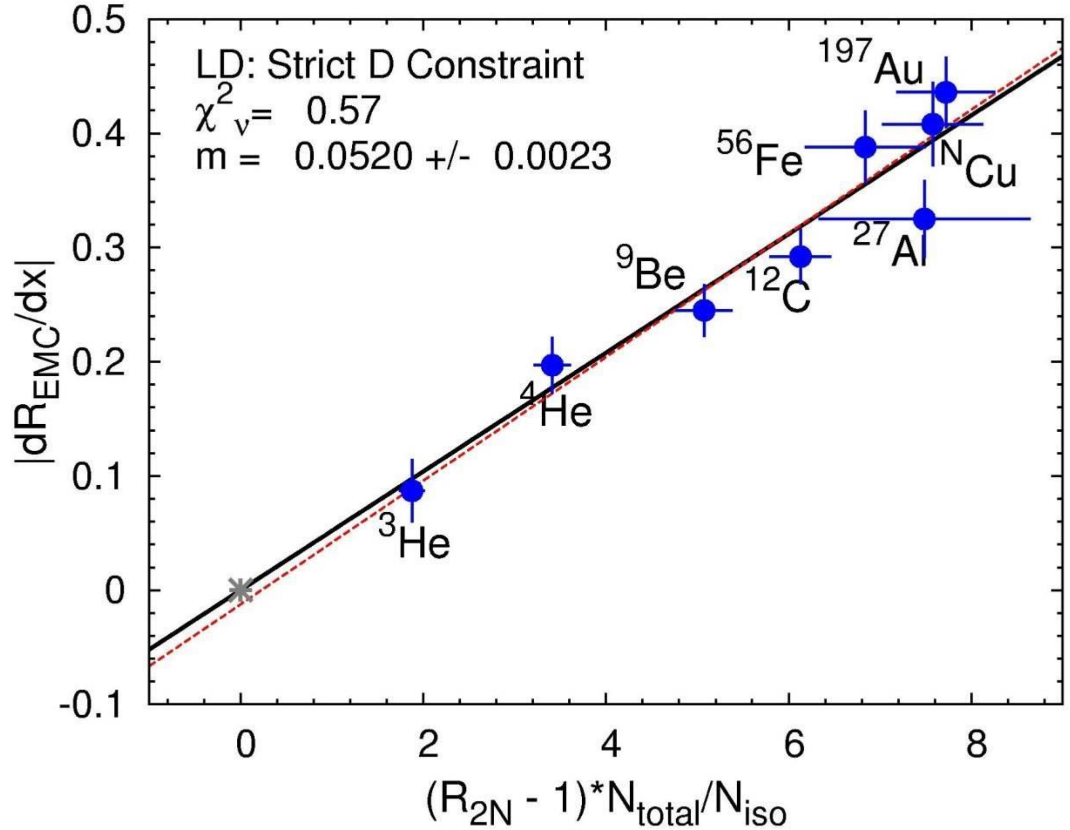




Analyses of last few years use the observation that the EMC ratio is a linear function of x between x=0.3 and 0.7



A density-dependent fit works for larger nuclei, but totally fails for light (A<12) nuclei



Number of pn SRC per nucleon

These observations ar argument that EMC effect is due to pn SRCs

Models have to address the paradox: evidence that EMC effect is predominantly due to SRCs while SRC are at least 90% nucleonic, while the EMC effect for x=0.5 is ≥15%

It appears that essentially one generic scenario survives <u>strong deformation of rare configurations in bound nucleons increasing with nucleon momentum and with most (though not all) of the effect due to the SRCs .</u>

An extreme assumption that EMC effect is present solely for SRC would require huge EMC effect at x=0.5 for EMC (SRC):

EMC inclusive / Prob. SRC ~ 0.10/0.2 ~1/2 for all SRC configurations

Current Rules of the game for building models of the EMC effect

- ***Remember baryon conservation law***
- ***Honor momentum conservation law***
- ***Don't introduce a noticeable number dynamic pions into nuclei***
- ***Don't introduce large deformations of low momentum nucleons***

Analysis of (e,e') SLAC data at x=1 -- tests Q^2 dependence of the nucleon form factor for nucleon momenta k_N < 150 MeV/c and Q^2 > 1 GeV^2 :

☛ $r_N^{bound}/r_N^{free} < 1.036$

Similar conclusions from combined analysis of (e,e'p) and (e,e') JLab data

Analysis of elastic pA scattering $|r_N^{\text{bound}}/r_N^{\text{free}} - 1| \lesssim 0.04$

Problem for the nucleon swelling models of the EMC effect with 20% swelling

two extra rules of the game based on SRC studies

- ***Don't introduce large exotic component in nuclei - 20 % 6q, Δ's***
- ***Honor existence of large predominantly nucleonic short-range correlations***

Generic models of the EMC effect

- extra pions: carry larger fraction of momentum:
  $\lambda_\pi \sim 5\%$ in nuclei than in free nucleon

  + results in enhancement from scattering off pion field with $\alpha_\pi \sim 0.15$

- 6 quark configurations in nuclei with $P_{6q} \sim 20\text{-}30\%$

- *Nucleon swelling - radius of the nucleus is 20--15% larger in nuclei. Color is significantly delocalized in nuclei*

  Larger size →fewer fast quarks - possible mechanism: gluon radiation starting at lower Q^2 $(1/A)F_{2A}(x,Q^2) = F_{2D}(x,Q^2\xi_A(Q^2))/2$

- Mini delocalization (color screening model) - small swelling - enhancement of deformation at large x due to suppression of small size configurations in bound nucleons with effect roughly $\propto k_{nucl}^2$ ➔ dominate contribution of SRCs

Very few models of the EMC effect survive when constraints due to the observations of the SRC are included as well as lack of enhancement of antiquarks and Q^2 dependence of the quasielastic (e,e') at x=1

- essentially one generic scenario (FS85) survives - strong deformation of rare configurations in bound nucleons increasing with nucleon momentum and with dominant contribution due to the SRCs .

Example: in the color screening model presented below modification of average properties is < 2- 3 %.

Dynamical model - color screening model of the EMC effect

Combination of two ideas:

(FS 83-85)

(a) QCD: Quark configurations in a nucleon of a size << average size should interact weaker than in average. Application of the variational principle indicates that probability of such configurations in bound nucleons should be suppressed.

(b) Quarks in nucleon with $x>0.5$ --0.6 belong to small size configurations with strongly suppressed pion field - while pion field is critical for SRC especially D-wave.

small admixture of nonnucleonic degrees of freedom due to small probability of configurations with $x>0.\underline{5}$ (~0.02) - hence no contradictions with soft physics)

In 83 we proposed a test of (b) in hard pA collisions. Finally became possible using data from pA LHC data then in 2013 on forward jet production confirmed our expectations that a nucleon with large x quark has smaller than average size

Introducing in the wave function of the nucleus explicit dependence of the internal variables we find for weakly interacting configurations in the first order perturbation theory using closer we find $\tilde{\psi}_A(i) \approx \left(1 + \sum_{j\neq i} \frac{V_{ij}}{\Delta E}\right) \psi_A(i)$

where $\Delta E \sim m_{N*} - m_N \sim 600 - 800\, MeV$ average excitation energy in the energy denominator. Using equations of motion for ψ_A the momentum dependence for the probability to find a bound nucleon, $\delta_A(p)$ with momentum p in a small size configuation was determined for the case of two nucleon correlations and mean field approximation. In the lowest order

$$\delta_A(p) = 1 - 4(p^2/2m + \epsilon_A)/\Delta E_A$$

After including higher order terms we obtained for SRCs and for deuteron:

$$\delta_D(\mathbf{p}) = \left(1 + \frac{2\frac{\mathbf{p}^2}{2m} + \epsilon_D}{\Delta E_D}\right)^{-2}$$

Estimating the effect of suppression of small configurations. Introducing in the wave function of the nucleus explicit dependence of the internal variables we find that probability of small size configuration is smaller by factor

$$\delta(p, E_{exc}) = \left(1 - \frac{p_{int}^2 - m^2}{2\Delta E}\right)^{-2}$$

effect ∝ virtuality

$p_{int} = p_A - p_{recoil}$

Four vectors

$$\Delta E = m_{N^*} - m_N$$

For small virtualities: $1-c(p^2_{int}-m^2)$

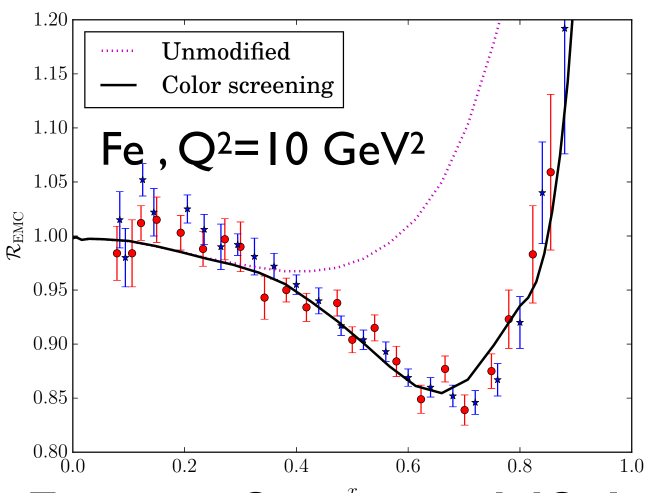
seems to be very general for the modification of the nucleon properties. Indeed, consider analytic continuation of the scattering amplitude to $p^2_{int}-m^2=0$. In this point modification should vanish. Still modification for S- and D- wave maybe different

Our dynamical model for dependence of bound nucleon pdf on virtuality - explains why effect is large for large x and practically absent for x~ 0.2 (average configurations V(conf) ~ <V>)

In the lowest order of perturbation over fluctuation the EMC effect is proportional to<V> in which SRC give dominant contribution but mean field is still significant - 30 -40%,

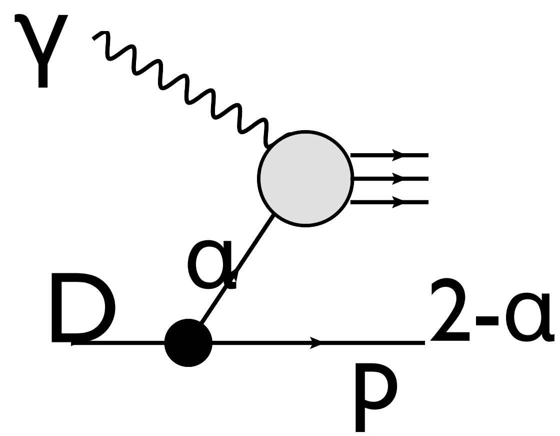
A-dependence of <V> is similar to that of the EMC effect (I.Sick)

Simple parametrization of suppression: no suppression x≤ 0.45, by factor $\delta_A(k)$ for x ≥0.65, and linear interpolation in between



Freese, Sargsian, MS 14

Tagging of proton and neutron in e+D→e+ backward N +X as a probe of the origin of the EMC effect (FS 85)



interesting to measure tagged structure functions where modification is expected to increase quadratically with tagged nucleon momentum. It is applicable for searches of the form factor modification in (e,e'N).

$$1 - F_{2N}^{bound}(x/\alpha, Q^2)/F_{2N}(x/\alpha, Q^2) = f(x/\alpha, Q^2)(m^2 - p_{int}^2)$$

Here α is the light cone fraction of interacting nucleon

$$\alpha_{spect} = (2-\alpha) = (E_N - p_{3N})/(m_D/2)$$

In practice, small background for 2- α >1, and in this kinematics one expects an EMC like effect already for smaller spectators momenta, since x/α > x.

Importance caveat: for large nucleon momenta nucleons closer to each other and chances of f.s.i maybe larger. Not the case in semi exclusive case eD—>e +p + "resonance".
But maybe relevant for larger W. Need dedicate studies of f.s.i. in DIS in the nucleus fragmentation region.

Optimistic possibility - EMC effect maybe missing some significant deformations which average out when integrated over the angles

A priori, deformation of a bound nucleon can also depend on the angle ϕ between the momentum of the struck nucleon and the reaction axis as

$$d\sigma/d\Omega/ < d\sigma/d\Omega >= 1 + c(p, q).$$

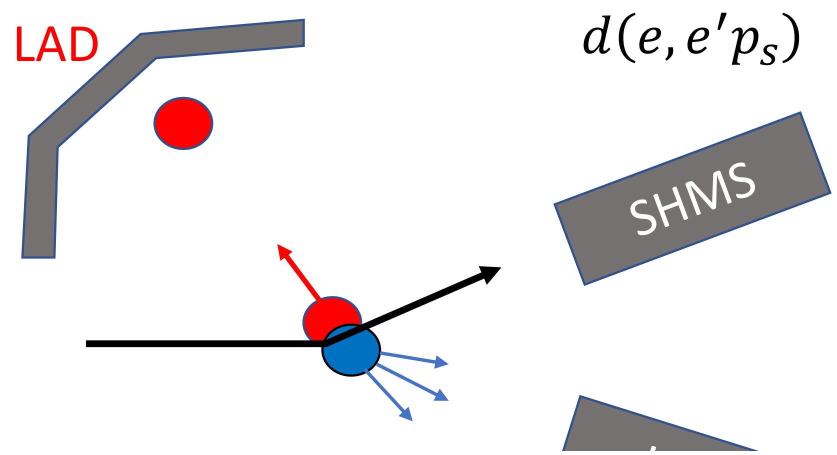
Here $<\sigma>$ is cross section averaged over ϕ and $d\Omega$ is the phase volume and the factor c characterizes non-spherical deformation.

Such non-spherical polarization is well known in atomic physics *(discussion with H.Bethe)*. Contrary to QED detailed calculations of this effect are not possible in QCD. However, a qualitatively similar deformation of the bound nucleons should arise in QCD. One may expect that the deformation of bound nucleon should be maximal in the direction of radius vector between two nucleons of SRC.

E12-11-107: The LAD Experiment

Spectator-tagged deep inelastic scattering:

- Bound neutron structure modification
- LAD will detect spectator protons 200 – 700 MeV/c
- Approved by PAC 38, for 40 days
- **Passed ERR in 2020**
- **Passed Jeopardy in 2021**



LAD will cover kinematics where FSI are small(backward + hadron formation fast)

and where FSI are large (~90o emission α~ 1)

To do list for EMC related topics

- ☞ Leading / HT separation in the EMC effect —- especially at x ~ 0.6 where Fermi motion effect is very different for LT & HT
- ☞ Tagged structure functions in eD
- ☞ Direct searches for non-nucleonic degrees of freedom like Δ-isobars
- ☞ Dedicated studies of f.si. in light nuclei

Conclusions

Last decade - impressive progress in understanding SRC in nuclei

☞☞ Next few years: tagged structure functions in eD to test critically the origin of the EMC effect , probing ultra high momenta in nuclei, three nucleon correlations, determining optimal formalism for description of relativistic dynamics.

☞ Two nucleon SRC - going from discovery to precision measurements